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METHODOLOGY AND MONITORING OF RADON, THORON AND THEIR DAUGHTERS

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MÉTHODES SERVANT À MESURER LES ÉMANATIONS DE RADON, DE THORON ET DE LEURS PRODUITS DE FILIATION

par

M.G. Townsend

RÉSUMÉ

Ce rapport présente une brève description des méthodes servant à mesurer les émanations de thoron et de radon gazeux et leurs produits de filiations dans le milieu de travail ou autres. Il contient de plus des renseignements portant sur l'échantillonnage pris au hasard, la surveillance continue, les mesures intégrées et la dosimétrie personnelle. Les erreurs contenues dans les différentes méthodes de mesure font l'objet d'une comparaison.

De plus, les aspects de l'étalonnage des techniques de mesure y sont décrits et des méthodes d'étalonnage inter-laboratoires sont suggérées. Un compte rendu sur les fractions libres et le "plateout" des produits de filiation est aussi présenté dans ce rapport. Les stratégies d'échantillonnage des différents milieux font l'objet d'une discussion et un tableau des règlements et des recommandations ayant trait aux mesures du rayonnement dans les pays membres de l'OCDE (Organisation de coopération et développement économiques) est fourni. On y souligne aussi les exigences en matière de formation sur la protection contre les rayonnements.

Enfin, on a décrit les directives concernant l'appareillage et les méthodes et procédures de surveillance dans les domaines où on possède suffisamment de renseignements et où il existe un consensus d'opinion.

ABSTRACT

Methods are described for monitoring radon and thoron gases and their daughter products in occupational and non-occupational environments. Grab-sampling, continuous monitoring, integrated measurements and personal dosimetry are discussed. Errors in different measurement methods are compared.

Calibration aspects of measurement techniques are described and procedures for interlaboratory calibration are suggested. An account of unattached fraction and plateout of radon daughters is included. Sampling strategies for occupational and non-occupational environments are discussed and a table of regulations and recommendations for monitoring radiation in countries of the OECD is provided. Radiation protection training requirements are identified.

Where sufficient information and consensus of opinion exist, guidelines on apparatus, methods and procedures for monitoring are developed.

1. INTRODUCTION

The NEA programme of work on Radon Dosimetry and Monitoring, as described by its terms of reference for both Phases I and II (SEN/SAN (79)23, SAN/DOC (82)10), is an integrated set of tasks which have emerged from discussions by the Committee on Radiation Protection and Public Health over recent years. It is based on the outcome of the NEA specialist meetings on dosimetry and monitoring of radon, and its daughter products at Elliot Lake, Canada, in October 1976, Paris/La Crouzille in November 1978, NEA International Symposium on "Management, Stabilization and Environmental Impact of Uranium Mill Tailings" Albuquerque, in July 1978, and also on relevant discussion at the Arlington Workshop on radiation protection for naturally occuring radionuclides, in May 1978.

The work is intended to provide further specialised guidance on dosimetry and monitoring for radiation protection from radon, thoron and their daughters, particularly in uranium/thorium mines, but also in non-mining situations for application to and fulfillment of the recommendations of the ICRP in this area (see Appendix 2).

2. OBJECTIVES OF REPORT

This report is submitted to the NEA Expert Group on Radon Dosimetry and Monitoring, as an aid to their work in Phase II. Its objectives are:

2.1 To identify and review the scientific and technical points covered by the Terms of Reference of the group of experts, Phase II: Metrology and Monitoring (1).

2.2 To focus the attention of the group on the issues requiring discussion in the preparation of a state-of-the-art report on this subject and to provide a framework for such a report.

2.3 To recommend further work needed to resolve outstanding problems.

3. RADON, THORON AND THEIR DAUGHTERS

Radioactive nuclei present in the atmosphere of uranium mines, uranium mills, non-uranium mines and buildings including houses may constitute a health hazard. The ultimate source of airborne radioactivity is uranium ^{238}U and thorium ^{232}Th. Their decay series are shown in Tables 1 and 2. Trace amounts of these elements and/or their decay products ^{226}Ra and ^{224}Th present in rocks, soils and in some building materials account for airborne radioactivity found in houses and non-uranium mines.

All members of the ^{238}U decay series, Table 1, are solids except for ^{222}Rn, radon, which is a gas. ^{222}Rn can diffuse from its local site of production, and from material close to the surface, some radon will escape to the air. The half-life of ^{222}Rn is 3.83 days; radioactive equilibrium between the succeeding daughters ^{218}Po(RaA), ^{214}Pb(RaB) and ^{214}Bi(RaC) occurs after approximately 3 hours. RaC decays to RaC', ^{214}Po, which has a very short half life (164 μs) and decays to long-lived ^{210}Pb which effectively blocks the decay chain (2).

In the decay chain originating with ^{232}Th, the corresponding gaseous member is ^{220}Rn or thoron (Tn).

While radon and thoron gases are alpha emitters, they do not accumulate significantly in the lung upon inhalation and are not in themselves a major health hazard. However, radon and thoron daughters are chemically reactive solids, and attach almost immediately to any particulate matter in

Table 1 - Principal decays from ^{238}U to ^{206}Pb

Common name or symbol	Half-Life	Principal radiations	Alpha energy (MeV)	Gamma-ray quanta per decay	Average gamma-ray energy (MeV)
Uranium I - ^{238}U	4.49×10^9 yr	α	4.18		
Uranium X_1 - ^{234}Th	24.1 days	β			
Uranium X_2 - ^{234}Pa	1.17 min	β			
Uranium II - ^{234}U	248000 yr	α	4.76		
Ionium - ^{230}Th	80000 yr	α	4.68 (75%)		
			4.61 (25%)		
Radium - ^{226}Ra	1602 yr	α	4.78 (94.3%)		
			4.69 (5.7%)		
Radon - ^{222}Rn	3.825 days	α	5.485		
Radium A - ^{218}Po	3.05 min	α	6.003		
Radium B - ^{214}Pb	26.8 min	β			
		γ		0.82	0.295
Radium C - ^{214}Bi	19.7 min	β			
		γ		1.45	1.050
Radium C' - 214Po	164 μs	α	7.69	1.0	0.047
Radium D - ^{210}Pb	22 yr	β			
		γ			
Radium E - ^{210}Bi	5.02 days	β			
Radium F - ^{210}Po	138.3 days	α	5.304		
Radium G - ^{206}Pb	Stable				

Table 2 - Principal decays from ^{232}Th to ^{208}Pb

Name/Symbol		Half life	Principal radiation	Alpha energy MeV
	^{232}Th	$\sim 10^{10}$ y	alpha	4.08
	^{228}Ra	6.7 y	beta	
	^{228}Ac	6.1 h	beta	
	^{228}Th	1.9 y	alpha	5.52
	^{224}Ra	3.64 d	alpha	5.79
Thoron,	^{220}Rn	55 s	alpha	6.28
ThA,	^{216}Po	0.15 s	alpha	6.78
ThB,	^{212}Pb	10.6 h	beta	
THE DECAY BRANCHES				
1. BRANCH				
ThC,	^{212}Bi	60.6 m	alpha (36%)	6.00
ThC",	^{208}Tl	3.1 m	beta	
ThD,	^{208}Pb	stable		
2. BRANCH				
ThC,	^{212}Bi	60.6 m	beta	
ThC',	^{212}Po	0.3×10^{-6}	alpha (64%)	8.78
ThD,	^{208}Pb	stable		

the atmosphere. Thus in mine air, particulate matter becomes radioactive by adsorption. The daughters, either attached or unattached, cause important radiological consequences when inhaled, as they tend to lodge in the lung mucosa. The retained daughters release alpha energy through the alpha-emitters RaA, RaC', ThC and ThC' to the cells of the epithelium.

The radiological effect of the inhaled radon or thoron daughters is dependent on where the daughters are retained in the respiratory tract and this depends on the degree of attachment of the daughters.

However, for most practical purposes, the radiological effect can be measured by the potential alpha energy delivered to the respiratory tract by decay of radon and thoron daughters.

A radon daughter working level has been defined as:

$$Rn(WL) = \frac{(7.68+6.0)(RaA) + 7.68(RaB) + 7.68(RaC)}{1.3 \times 10^5} \qquad (i)$$

where (RaA), (RaB) and (RaC) are the concentrations in atoms per litre of the daughters. In the denominator of the right hand side of equation (i) 1.3×10^5 is the alpha energy in MeV for the complete decay to ^{210}Pb of radon daughters in equilibrium with radon gas of activity 100 pCi/L, i.e., where the activities of RaA, RaB, RaC and RaC' are 100 pCi/L. The numerator of the right hand side of (i) represents the potential alpha energy of decay to ^{210}Pb of the radon daughters in the atmosphere to be assessed. In the numerator the alpha energy of decay of RaA contains 2 terms: 6.0 MeV corresponding to alpha emission from RaA and 7.68 MeV for alpha emission from RaC' which is formed subsequent to the decay of RaA. Similarly, while RaB and RaC are not alpha emitters they contribute a term to (i) due to their decay through RaC'. RaC', itself, has a very short half-life, 164 μs, and is therefore always in equilibrium with RaC. Its concentration in atoms/L is always low so that the number of RaC' atoms inhaled, and consequently the energy dissipated by these atoms, is negligible. (RaC') therefore does not appear in the numerator of (i). Evidently, from (i) for an atmosphere containing 100 pCi/L for each of RaA, RaB and RaC, WL = 1.

An exposure of 1 WL for a working period of one month (170 h - in some countries 173 h) is defined as one working level month, 1 WLM.

Thoron has a half-life of 54 s; thus its rate of diffusion from rock or building materials is much less than that of ^{222}Rn. However, thoron daughters ^{212}Pb(ThB) and ^{212}Bi(ThC) have half-lives of 10.6 h and 1.01 h, respectively, and appreciable concentrations can occur in mine atmospheres.

Recent estimates of the relative contribution to lung dose of thoron daughter alpha emission are much higher than earlier estimates (3) and, because of the presence of high thorium concentrations coexisting with some uranium ores in certain parts of the world, monitoring both radon and thoron daughter concentrations may be necessary.

A thoron daughter WL has been defined as:

$$Tn(WL) = \frac{7.8\,[(ThB) + (ThC)]}{1.3 \times 10^5} \qquad (ii)$$

where (ThB) and (ThC) are the concentration in atoms/litre of the thoron daughters ^{212}Pb and ^{212}Bi.

A third isotope ^{219}Rn, actinon, is part of the ^{235}U decay chain. The low natural abundance of ^{235}U and the short half-life (4.0 s) of actinon ensures that actinon generates no health hazard.

Most national regulations and recommendations for radon daughter monitoring (Appendix 2) require only the measurement of WL. Hence WL is the most important quantity to be measured and, as discussed later, a measurement of WL can be made directly using a single gross-alpha count method. However, for a more complete description of the radiological hazard, i.e., for applying data to various dose models or for research purposes, measurement of other quantities such as radon gas concentrations, individual daughter concentrations and unattached fractions are of interest. A more detailed account of the objectives and scope of monitoring is given below.

4. OBJECTIVES AND SCOPE OF MONITORING OF RADON, THORON AND THEIR DAUGHTERS

4.1 General

Measurement and monitoring objectives in radiation protection are predominantely to assess the radiation exposure of the individual, to ensure that safe working and environmental conditions are maintained and to show compliance with prescribed limits.

Radiation exposure below regulatory limits can be achieved and maintained by monitoring and control. These limits are based on estimates of detrimental health effects. Control by ventilation and other techniques below these limits is based on measures which are reasonably achievable taking into account economic and social factors (4,5). In Canada and some other countries, the annual occupational exposure limit is 4 WLM (see Appendix 2). It has been recommended that cumulative exposure shall be determined by a procedure that yields an annual exposure having an experimental error no greater than 50% at 95% confidence level (5,6).

Monitoring programs allow the evaluation of the effectiveness of environmental control measures e.g., ventilation (7,8). Results from these programs are of potential use in future scientific investigations (10).

A more detailed discussion of general objectives and requirements for measurement and monitoring of radon, thoron and their daughters in different environments has been carried out during Phase I of the work of the OECD-NEA Group of Experts, Task Group 3 (see ref. 9).

4.2 Practical radiation protection

4.2.1 Occupational exposure

Problems with potentially increased occupational exposure due to inhaled radon, thoron and their daughters may occur in mining environments (uranium- and non-uranium underground mines, open pit mines), uranium- and thorium mills, underground installations (hydro-electric power stations, military defence installations, tunnels) and radon spas.

The main reasons for elevated atmospheric radon, thoron and daughter-concentrations at these sites are radon and thoron emanating from soil, ore or radon-rich water. The varying contribution of these components causes temporal and spatial fluctuations of the atmospheric nuclide concentration levels, which together with the varying exposure conditions (occupancy time, degree of physical activity), can result in large variations of the dose to different individuals.

The objectives of monitoring programs in practical radiation protection are aimed at preventing overexposure to radon, thoron and their daughters in compliance with national standards, to check on technical or organisational countermeasures and to identify radon/thoron sources. This can be achieved in three stages:

Stage 1 - Screening: All work places are investigated in order to identify those sites with actually or potentially elevated atmospheric nuclide concentrations. This may represent a relatively large number of samples in order to provide base-line data. Furthermore the number of workers, the times spent at different locations and the corresponding physical activities should be recorded. The results from this stage enable the establishment of a first approximate dose assessment and permit the definition of a sampling pattern.

Stage 2 - Improved dose determination: At the work sites identified under stage 1 monitoring on a random basis should be carried out. For a more detailed description of a random sampling strategy see Section 10. The aim of this stage is to obtain a more accurate dose assessment to aid in the decision on compliance for safety standards (for statistical procedure, see Section 10) as well as on the necessity of countermeasures to reduce overexposure.

Stage 3 - Detection of radon- and thoron sources: Application of the ALARA ("as low as reasonably achievable")-principle by the International Commission on Radiological Protection (ICRP) requires that, in addition to the maintainance and achievement of safe and satisfactory working conditions, sources of unnecessary radiation exposure should be reduced with reasonable means, wherever possible. The monitoring of the various identified radon/thoron sources will allow for checking of the performance of countermeasures introduced under stage 2 and assist in the prevention of potentially unnecessary expenditures, e.g. increased ventilation.

In the case of new constructional operations it is necessary to obtain reference data on natural background levels at the site before the actual operational activities commence.

Furthermore changes of established technical work routines may require the re-assessment of the relevance of the adopted monitoring program.

4.2.2 Non-occupational exposure

Non-occupational exposure to radon, thoron and their daughters is mainly due to the inhalation of air in buildings. The main sources of radon and thoron in the indoor environment are exhalation from the surrounding subsoil, building materials, radon-rich water and natural gas.

Recent trends to conserve energy or use alternative sources of energy generally cause an increase of radionuclide levels in the indoor air due to reduced ventilation, the use of combined solar-bedrock storage heating systems or underground building designs. Similar to the objectives in practical radiation protection concerning occupational exposure, a stepwise approach is recommended:

Stage 1 - Screening: Due to the different source terms contributing to the indoor radionuclide levels, large scale screening surveys should be carried out in order to identify problem areas. The criteria for this screening program can be the use of special construction materials in the buildings, geological conditions of the subsoil, the use of radon-rich water, etc. With these data, a frequency distribution of the indoor nuclide concentration values can be obtained, signifying the magnitude of the number of buildings with potential radiation problems.

Stage 2 - Improved data assessement: In the problem area, as identified in the screening stage, random monitoring will provide statistically significant long-term mean values on indoor radon/thoron daughter levels needed for checking on the compliance with set standards (national regulations, clean-up criteria), and the need for technical countermeasures in order to reduce undesirably high radionuclide levels.

Stage 3 - Monitoring

of countermeasures: After the introduction of countermeasures (auxiliary ventilation, application of sealants or barriers, blocking of routes of radon entry, replacement of subsoil), it will be necessary to monitor the efficiency of the method employed.

4.3 Research applications

4.3.1 Improved dose assessment

In the case of research application, parameters in addition to those determined for practical radiation protection should be measured to improve the accuracy of the dose assessment. Independent of the dosimetric model applied, the calculation of the dose to the lung from the WLM-exposure requires data on the following:

- biological parameters of the exposed subject:

  mucus layer thickness
  depth distribution of the basal cells in the bronchial epithelium
  clearance characteristics
  respiratory minute volume (rmv) for specific physical activity,
  age,
  sex.
- physical parameters of the atmosphere inhaled:
  concentration of potential α-energy in air,
  equilibrium factor,
  particle size distribution of attached aerosol,
  hygroscopic growth of particles inhaled.

It can be shown that for a given age and sex of the exposed subject the relationship between Working Level Month (WLM)-exposure and dose to the basal cells in the bronchial tree is influenced primarily by the rmv, the particle size distribution of the attached aerosol and the fraction of the WLM due to free ions (10). Biological parameters are of secondary importance in the assessment of the dose to the basal cells averaged over the bronchial epithelium as well as the effective dose equivalent per WLM exposure.

For research applications, such as radiobiological interpretation of effects in animal inhalation or epidemiological investigation of lung cancer incidence in man, the following should also be taken into account:

- biological variability amongst the exposed species
  (ratio nose/mouth breathing, target geometry in respiratory tract, clearance processes),
  nature of carrier aerosols and presence of known or suspected synergistic factors (condensation nuclei, cigarette and diesel smoke, acid fumes, ore dust).

These variables can cause a regional and radionuclide-specific dose distribution in parts of the lung and thereby influence the dose/exposure conversion factor (10).

4.3.2 Radon transport pathways

Research on the mechanisms of radon and thoron exhalation from their sources and migration along different pathways is needed in order to optimize countermeasures such as ventilation control or development of radon barriers and sealants. For studies, such as investigation of radon migration from the subsoil into dwellings or from the orebody into mine atmosphere, the measurement of the following parameters is necessary:

- characterization of the radon/thoron source:
  uranium, radium (^{226}Ra), thorium (^{232}Th) concentration in the medium (soil, ore, building material, water),
  particle size of matrix,
  emanating fraction,
  porosity of material,
  influence of meteorological parameters on exhalation rate (humidity, barometric pressure gradient, temperature, etc.),
- diffusion characteristics,
- active transport mechanisms through medium,
- active and passive ventilation - and filtration rate in given volume (room, mine gallery, stope, etc.).

5. MEASUREMENT OF RADON GAS

While most national regulations (Appendix 2) require measurement of WL rather than radon gas concentrations, monitoring the latter can be useful since radon levels reflect an upper limit for the potential alpha energy of air-borne radon daughters. In addition, radon can often be monitored more easily than WL. Thus atmospheres with high air-borne radioactivity can be detected readily by monitoring radon concentrations. Methods for measuring radon gas concentrations may be grouped into three general categories: grab-sampling, continuous monitoring and long-term integrated measurements.

5.1 Grab-sampling of radon

This may be carried out by means of a ZnS (Ag) coated scintillation cell originally developed by Lucas (11,12). A sample of the air to be examined for radon content is collected by opening a previously evacuated container in the sampling area and resealing the container. The radon is then later (possibly days later) concentrated either by collection on glass beads maintained at liquid nitrogen temperature or by adsorption on charcoal at dry ice temperature; it is then transferred to the scintillation cell. For high radon concentrations, as in some mining environments, scintillation cells may be filled directly from the air. Scintillation cells are coated on the inside with ZnS(Ag), except for a clear end window of quartz, glass or plastic. The cells are placed on top of, and with the end window in direct contract with, a photomultiplier tube in a light-tight enclosure. Over a period of approximately 3-4 hours the radon in the cell grows into a state of transient equilibrium with its short-lived daughters. Alpha particles emitted from radon and RaA and RaC' strike the zinc sulphide and give rise to light pulses. These are converted in a photomultiplier tube to electrical pulses which may be counted by a discriminator/scaler. The activity of the cell grows over the same period and, subsequently, decays with the half-life of radon.

An integrated count method has been described, where the counting of the radon activity may start at any time after filling of the cell with daughter-free air (13). The accuracy of the method is shown to depend on the length of the counting period rather than upon the time elapsed since sampling. The normal procedure, however, is to wait 2-3 hours after sampling before the activity is counted. Since in the equilibrium state the decay of each radon atom gives rise to the emission of three alpha particles, the

theoretical conversion factor is $3 \times 3.7 \times 10^{10}$ counts per second per curie or 6.6 cpm/pCi. The efficiency of most cells is about 70-80% corresponding to conversion factors of 4-5 cpm/pCi. It should be stressed, that although it is possible to manufacture scintillation cells with very little spread in the conversion or calibration factors, "home made" cells should always be individually calibrated if an accuracy higher than 10-20% is required. Calibration is discussed in section 9.1.

A cell, which has been newly used, even when evacuated, shows a background activity from plated out radon daughters of about 30-50% of the actual activity. This background activity, however, decays with an effective half-life of approximately half an hour. The short-lived radon daughters, on their way to the stable end product ^{206}Po (RaG), pass through the long-lived ^{210}Pb (RaD) and ^{210}Po (RaF), with half-lives of 22 years and 136 days, respectively. Since the latter is also alpha active, scintillation cells during use gradually acquire a lasting background activity and the cells may eventually have to be recoated and recalibrated. The volume of most scintillation cells is approximately one hundred to several hundred cm^3. Owing to the short range of alpha particles in air at atmospheric pressure, little is gained in sensitivity by increasing the counting volume. Consequently, activities below approximately 1 pCi/L can only be measured with a considerable uncertainty, when sampling directly in the scintillation cells.

Cells with higher sensitivity and lower background have been developed for laboratory use (14,15). In these, the scintillator or surface barrier detector is covered with a thin metallic foil, to which a high negative potential is applied in order to collect the positively charged RaA atoms initially produced. Since the effective counting volume may be considerably larger than in ordinary scintillation cells, the sensitivity may be as high as 0.01 pCi/L. Although in this method radon daughters are responsible for the majority of counts, radon atoms decaying in the vicinity of the detector may also contribute counts.

An alternative method to the Lucas cell method is the two-filter procedure (16). Here the radon concentration is deduced from a pure radon daughter count. Air is drawn, at a typical rate of 10 L/min and usually for a period of 5 min, through a cylinder with a filter on either end. The front filter removes all daughters in the air sampled, and the second filter collects those daughter products (almost only RaA) produced by decay of radon in

the air, while it passes down the cylinder. The alpha activity from the filter after sampling is then a measure of the radon concentration in the sample air. Although the sample volume is fairly large, typically 50 litres, the activity collected on the downstream filter is relatively small, and hence the accuracy rather poor. Furthermore the method has been shown to be humidity dependent (17).

Because of its short half-life (54 s), thoron gas, ^{220}Rn, is not generally monitored. However, several measurement techniques have been described (18). One method is to use large highly-sensitive 2-filter tubes (19). The transit time of the air through the tube must be kept to less then approximately 6 s, necessitating a large pump (12).

5.2 Continuous monitoring of radon

In atmospheres where there are rapid and significant fluctuations in radon gas concentration, continuous monitoring of radon gas may be preferable to grab-sampling. Continuous monitoring of radon concentrations is probably the most useful method for studying the effects of ventilation on radon levels, and also for the determination of average radon concentrations. Several continuous radon monitors have been developed (20,21,22,23).

Radon gas concentrations can be measured continuously more easily than radon daughter concentrations. Because loss of activity by plateout is not a problem, the electronic and mechanical equipment for sampling and analysis can be located away from the sampling location. The sample can be drawn long distances from an actual work area through inexpensive tubing that will be unaffected by dust, water vapour and other conditions that affect radon-daughter sampling. The sampling flow rate is also not critical for radon gas measurement since the sample concentration is not affected by flow rate.

Continuous methods can adapt the grab-sampling methods described above to automatic operation. Continuous monitors based on ZnS scintillation cells are commercially available. Air is pumped through a filter that removes daughters, then through the scintillation cell. Counts are recorded from decay of ^{222}Rn as well as from daughters formed in the cell. As is the case for grab-sampling, radon grows into equilibrium with its daughters over a period of 3-4 hr and the instrument will thus show a delay in response to changes in the radon concentration of the same order. The daughters tend to plateout on the walls of the cell so that the count total for any period

arises partially from earlier radon concentrations. Busigin et al. (24) and Thomas et al. (24a) have used the counts in previous counting intervals for correcting the actual count rate. These instruments have sensitivities in the 1 pCi/L range.

An instrument of this type has recently been used for continuous measurements in an energy-efficient house where the ventilation rate was being varied (25).

Droullard (26) has reported some results for a continuous radon monitor. He also monitors radon daughters simultaneously with a beta detector (see Section 6.3). Chittaporn, Eisenbud and Harley (27) use a negatively charged electret for removing the initially positively charged RaA-atoms from the counting volume.

Continuous radon monitors based on the two-filter method have been developed (28,29). Other continuous monitors use electrostatic collection of daughters by a negative potential at a detector which may be a ZnS(Ag)/photomultiplier detector covered with aluminized mylar to act as an electrode (23) or a semiconductor device held at a high voltage (28).

5.3 Time-integrated measurements of radon

Although continuous monitoring gives the most detailed information on radon concentrations in a given location, it is often sufficient to determine the time-averaged concentration over the period in question. Many instruments for such time-integrated measurements have been developed (17,29, 30,31,32). Most of these instruments use either track-etch detectors of cellulose nitrate or polycarbonate, or thermoluminescent detectors (TLD).

In most track-etch devices the film is placed in a small cup to which the sample air has access through a diffusion barrier. The barrier serves the dual purpose of filtering out radon daughters and slowing down the rate of air admittance. Thus any thoron present in the sample air has effectively decayed before the air enters the cup and consequently only radon and the stable gases are admitted (33,34). Alpha particles from radon as well as from its daughters, produced in the cup, cause radiation damage tracks in the film. After exposure the tracks are made visible either by chemical or by electrochemical etching (33). The latter method offers the advantage of large track diameters, simplified track counting and track stability against modifying environmental factors like elevated temperature and humidity.

In one procedure (29) of a TLD system the disc is placed a short distance from the surface of the second filter in a two-filter device. Sample air is drawn continuously through the system, at a low rate (about 3 L/min), by a pump which can be either line or battery operated. The limit of detection is as low as 0.05 pCi/L for an exposure of one week.

In another method (31,32) the radon diffuses into the detector volume through a porous barrier which filters out radon daughters. Positively charged RaA ions formed by decay within the detector volume are concentrated onto a small foil by electrostatic collection using a negative voltage of magnitude up to 1000 V. A TLD detector located directly behind the foil records the alpha activity of the daughter products. Beds of silica gel are used to reduce the moisture content of the air in the detector volume, since the collection efficiency of the system decreases with increasing humidity. This is probably due to a corresponding decrease in the mobility of the RaA-ions. A second TLD chip can be used to monitor the gamma background.

5.4 Exhalation of Radon

The process by which radon diffuses to air from radium-bearing materials (building materials, soil or mine walls) is called exhalation. The radon concentration in a given room or mine tunnel depends on the rate of radon diffusion into the room or tunnel. Consequently, in order to be able to predict upper limits for radon and radon daughter levels, it is necessary to know, among several other parameters, the exhalation rate of the walls, ceiling and floor. The exhalation rate from a given surface can be measured by sealing a can, open at one end, onto the surface and measuring the growth of radon activity in the can. This is generally carried out by taking grab samples of the air. This accumulator method has been used extensively, for measurements of soil exhalations as well as for measurements on walls (35,36, 37,38).

It should be emphasized, that the exhalation rate from the surface decreases as the activity in the can grows because of back-diffusion. Since in practice only exhalation into a virtually radon free room is of interest (free exhalation), only the initial part of the activity growth curve should be used in determining the exhalation rate.

When the exhalation rate from a limited sample of material is required, the sample is placed in a closed container and the growth of radon activity in the container is determined as described above (37,38). On occasion, results of exhalation rate measurements on smaller samples must be scaled up to larger amounts of material, i.e., walls. It should be noted, that when all dimensions of the exhaling item are considerably larger (~ 2-3 times) than the diffusion length of the material, the total exhalation is proportional to the area of the exhaling surface. The rate is then expressed in activity, or atoms per unit time per unit area, i.e., area exhalation rate. However, in the case of dimensions smaller (~ 1/2) than the diffusion length, the total exhalation is proportional to the exhaling mass or volume, and the rate is expressed in activity, or atoms, per unit time per unit mass, i.e., mass exhalation rate. For exhalation from walls, tiles, bricks etc. the latter conditions usually apply.

6. MEASUREMENT OF RADON AND THORON DAUGHTERS

There are three types of measurement of air-borne radon and thoron daughters: grab-sampling, continuous monitoring and personal dosimetry. Most methods require that a given volume of the air to be examined is drawn through a filter in a known time, and that the radon (thoron) daughter activity on the filter be counted during and/or after sampling. Filter efficiencies and self-absorption factors are discussed in (40). High efficiency materials such as membrane filters have a pore size less than 1 μm. Polystyrene filters and glass-fibre filters seem to be satisfactory but the type chosen may depend on local conditions.

Generally daughters are monitored by alpha counting but some procedures use beta counting and others employ a combination of alpha + beta. Individual daughter activities, for example alpha radiation from RaA, RaC', ThC and ThC', or gross activities such as alpha radiation from (RaA + RaC' + ThC + ThC') may be monitored.

Radon and thoron daughter concentrations on the filter may be related to radon and thoron concentrations in the atmosphere by a series of linear differential equations (2).

Equation (1) in Section 3 would appear to imply that determination of Rn(WL) requires measurement of three radon daughter concentrations. However, in certain experimental situations, there are relationships between

individual radon daughter concentrations. These lead to simplified two-count and one-count methods. These simplifications introduce some implicit approximation and, inevitably, some inherent error.

6.1 Grab-sampling of Radon Daughters

There are a number of errors and uncertainties associated with the different methods of grab-sampling of radon daughters. In this report an attempt is made to compare these different methods by comparison of their respective errors and uncertainties. Some of these errors are discussed in the following.

6.1.1 Errors in Grab-sampling of Radon Daughters

The errors in grab-sampling techniques have been systematically listed by Schiager et al. and one- and two-count methods have been compared according to their overall error (4). Principally it must be determined whether a specific grab-sampling method can meet the criterion of determining the annual accumulated exposure of each miner within 50% at 95% confidence level. In addition to the inherent error U(A), there is an uncertainty due to precision: the statistical counting error U(P), which is proportional to $\frac{1}{\sqrt{n}}$, where n is the number of counts. There are errors in flow rate or efficiency of the detector; these are likely to be smaller than U(P) for low radioactivity concentrations. There are uncertainties due to human error U(H), through unintentional mistakes made by the operator, e.g., timing of the sampling interval, which has a direct influence on the volume of air collected.

There are uncertainties common to all methods including temporal changes in radon daughter concentrations, U(C). Data on variability are available from the U.S. Bureau of Mines, Twilight Mine at Uravan, Colorado, and elsewhere (41). There is an error due to an occupancy factor U(O): uncertainties in exposure rate measurements and in exposure time estimates are considered to be independent of each other; however both must be determined to obtain a valid estimate of uncertainty for the cumulative exposure. Finally, an uncertainty due to record keeping U(R) is defined: the possibility that location, working level, or occupancy time could be incorrectly transcribed. As can be seen from Table 3, inherent error, precision and human mistakes are not the major causes of uncertainty in the grab-sampling approach to dosimetry (4). The principal contribution comes from fluctuations in the concentration of radon progeny within a stope or work area (4).

Table 3 - Summary of uncertainty parameters for 1- and 2-count radon daughter measurements (taken from reference (4))

Method	U(A)	U(P)			U(H)	U(C)	U(O)	U(R)	U
		1.0 WL	0.3 WL	0.05 WL					
Kusnetz 5-40-2	9a	3.3	6.0	15.0	2	36	4	1.5	38
Kusnetz 5-90-2	10	5.1	9.3	23.0	3	36	4	1.5	39
Rolle	13*	1.4	2.6	12.0	1	36	4	1.5	38*
Shreve original	15	2.8	5.1	13.0	4	36	4	1.5	39
Shreve corrected	6	2.8	5.1	13.0	4	36	4	1.5	38
Shreve optimized	4	3.0	5.5	25.0	4	36	4	1.5	37
Hill alpha ratio	10	26.0	47.0	116.0	2	36	4	1.5	60
Hill optimized	13	7.0	13.0	31.0	2	36	4	1.5	41
J-S alpha ratio	16	0.8	1.4	3.6	1	36	4	1.5	39
J-S optimized	13	1.5	2.7	6.7	1	36	4	1.5	39
HBS[45]	6	1.4	2.6	6.3	1	36	4	1.5	37
Two-count alpha spectroscopy II	16	1.1	2.0	4.5	1	36	4	1.5	39

a = All uncertainties are expressed as per cent

* = These values are modified from those given in reference (4). In fact 2-dimensional analysis now suggests that, for shorter delay times, U(A) is closer to 8% (46a).

U(A) = uncertainty due to accuracy based on inherent errors of method

U(P) = uncertainty due to precision based on counting statistics

U(H) = uncertainty due to human mistakes

U(C) = uncertainty due to temporal fluctuations in mine atmospheres between measurements

U(O) = uncertainty due to estimation of occupancy time

U(R) = uncertainty due to record keeping and data transcription

U = combined uncertainty

Errors are treated as independent and combined by summing their squares: total error = $(U(A)^2 + U(P)^2 + ...)^{1/2}$.

Most errors do not vary greatly for the different one- and two-count methods. However, inherent error varies significantly according to the method and it is used primarily here to compare different methods. The statistical error can always be reduced by increasing the count and/or sample time. While, in the following discussion, methods are often described according to rigid sample, wait and count times, in the CANMET laboratory we have tended to optimise the techniques for longer counting times of 10 to 15 min. In this more general interpretation of the one count methods, the Rolle technique, for example, signifies an early count and the Kusnetz technique a later count after 40 min. For these longer count times, statistical errors, in a typical mine atmosphere (~0.1WL), are ~4% compared to inherent errors of 10% or more.

6.1.2 One-count methods

One-count methods are important in mines because of their simplicity. There are two methods: Kusnetz (42) and Rolle (43). The Kusnetz method employs an air sampler (pump and filter) and an alpha-counter which is usually a scintillation device. For mining applications, normally 10 L of air is passed through the filter at 2 L/min. After a specified delay, ranging from 40 to 90 min, gross alpha counts are integrated within a counting interval of 1 to 5 min. Working Level is then computed by:

$$WL = \frac{\text{Net } \alpha\text{-counts}}{\epsilon . F . T_c . T_s . K}$$

where, ϵ = absolute counting efficiency, F = pump flow rate in L/min, T_c = count time, T_s = sampling interval in minutes, K = Kusnetz conversion factor (cpm/WL).

The Rolle method is similar to the above but the count period begins between 1 and 6 min after sampling, depending on the length of the count period: the delay time, T_w, decreases with increasing count time. This method is used widely in Australia and generally could be more useful because of its short delay time (12). In the mine it is not always convenient to wait 40 min after sampling before counting and many more samples can be measured

in an 8-hr shift with an early count. Furthermore, it is essential to use the Rolle method when thoron daughter WL are comparable with radon daughter WL as can occur, for example, in Alaska, Canada or Norway. This is discussed in section 6.2.

The relative accuracy of the two techniques has been a subject of much study. Rolle and Holub use different methods to estimate inherent error.

In Fig. 1, Rolle takes curves M and N for the limiting boundaries on the daughter activity ratios likely to be encountered in a mine (45). N represents the decay of radon in an isolated system. M represents mixing of very young air, where RaB and RaC concentrations are approximately zero, with old air in which equilibrium has been established: $\lambda_A N_A = \lambda_B N_B = \lambda_C N_C$, where λ_A, λ_B and λ_C are the daughter decay constants and N_A, N_B and N_C are the concentrations of RaA, RaB and RaC.

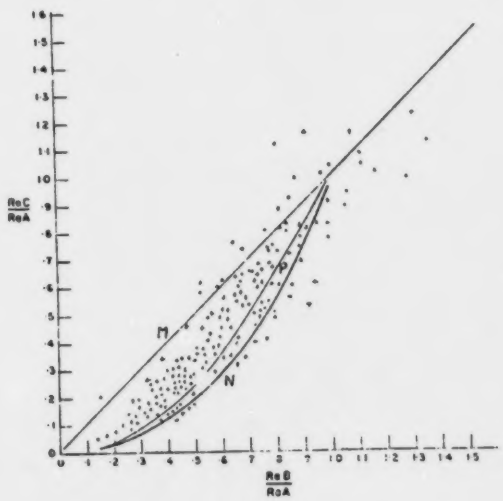

Fig. 1 - Growth of radon daughters in isolated system (N), mixing of young air and equilibrium air (M); mine-tunnel model (P); experimental points indicated

A number of data points measured by several workers lie mainly between these curves (Fig. 1) (45,46). For a given delay time after sampling, T_w, K is calculated for all activity ratios lying between curves M and N. The maximum and minimum values of K are then plotted as a function of T_w. An average K_a is then obtained and the uncertainty in K_a is given by:

$$\Delta K_a = 100(K_a - K_{(min)})/K_a \ \%$$

A study of ΔK_a as a function of T_w permits an optimum choice of T_w to give minimum error on the estimated WL. Figure 2 shows a plot of ΔK_a against T_w, for T_s (sampling time) = 15 min, and T_c (counting time) = 10 min.

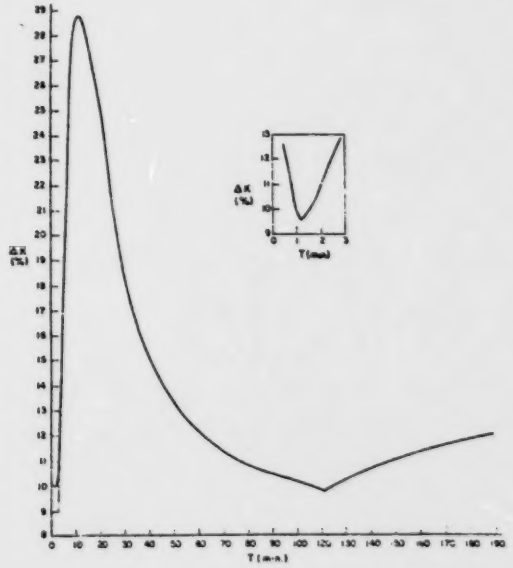

Fig. 2 - Inherent uncertainty in K versus waiting time, T_w, T_s = 15 min, T_c = 10 min (58)

Here the minimum ΔK at 1.2 min (±10%) is lower than the minimum (±15%) at 40 min. The early minimum occurs at the end of the RaA decay and the beginning of RaC growth. There is a certain symmetry in the duration of the three time periods: if T_s and T_c are interchanged and the time from end of sampling to the beginning of counting period remains constant, the Kusnetz

factor K stays the same (43,44). There is an empirical relation between wait time and count duration (58); however, it is preferable to optimise the wait-time for a suitable sampling and counting period using a reliable computer program.

Holub chooses to plot the radon daughter concentrations in a different way, Fig. 3.

In Fig. 3 the lower left-hand corner corresponds to pure RaA and also to "youngest air". Pure RaC is at the upper left-hand corner and pure RaB is at the right-hand corner. All points on his diagram correspond to 1 WL. As an example on Fig. 3 we have plotted the equilibrium point (+), RaA = 100 pCi/L, RaB = 100 pCi/L and RaC = 100 pCi/L. It should be noted that the position of this or any point is fixed by location on any pair of the axes: RaA and RaB, or RaB and RaC or RaC and RaA, i.e., there are only two degrees of freedom - a constraint being introduced by fixing each point at 1 WL.

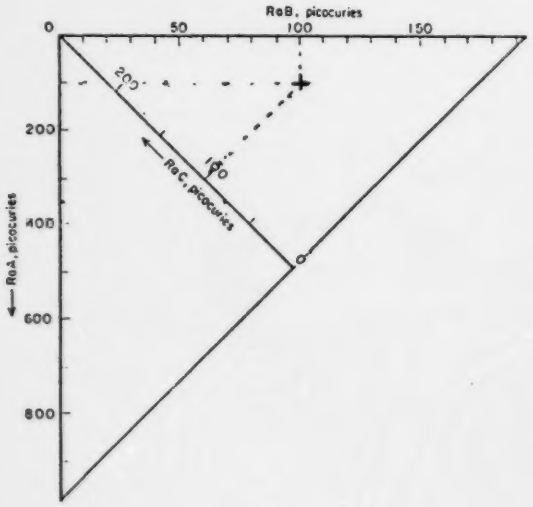

Fig. 3 - Triangular graph for displaying distributions of airborne mixtures of RaA, RaB and RaC. Equilibrium point (+) ((RaA) = (RaB) = (RaC) = 100 pCi/L) is shown

The question then arises, how does one locate a point when the WL is not equal to 1. This is best answered with an example: suppose one has 3 radon daughter activities and one calculates from equation (i) in Section 3,

a working level of 0.25 WL. In order to make the WL = 1, and at the same time retain the radon-daughter activity ratio, one must multiply each activity by 1/0.25 = 4. One can then plot the scaled-up activities using any pair of axes. In this report the arbitrary choice of axes, RaA and RaB, is made.

In Fig. 4 some 385 experimental points collected by a number of workers in underground mines are shown (44,45). Error contours for the Rolle technique with T_s = 10, T_w = 4.4 and T_c = 5 min are also shown (44,45). These are calculated by taking the activities represented by each location in the triangle and simulating by means of a computer program, the Rolle count. Now, the Rolle method counts gross alpha particles on the filter for 5 min; it is only an approximate method and involves an inherent error. Thus the answer calculated in the computer (EWL) for a particular activity ratio by the Rolle method will not quite equal the true WL(TWL) which is always 1. The per cent error is calculated from:

$$\% \text{ error} = \frac{\text{EWL} - \text{TWL}}{\text{TWL}} \times 100$$

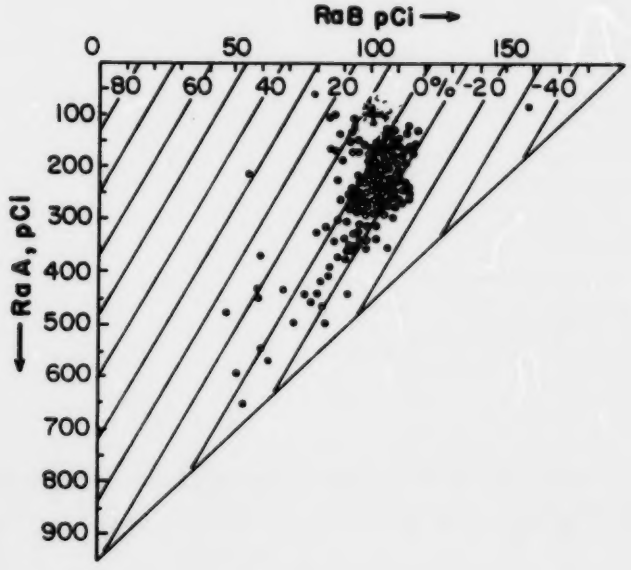

Fig. 4 - Errors estimated for Rolle technique T_s = 10, T_w = 4.4, T_c = 5 min (43,46). Equilibrium point (+) is shown

Contour lines are drawn through values of equal inherent error, Fig. 4.

As an example, the equilibrium activity concentration (+) on Fig. 4 would be calculated by the Rolle method as ~ 1.06 WL i.e., the error would be +6%.

Similar errors for a Kusnetz count with T_s = 5, T_w = 40 and T_c = 5 min are shown in Fig. 5. Holub estimates the inherent error by finding the error intervals (contour lines) that enclose a given fraction (90%) of mine data. Although the contour lines run parallel to the data in the case of the Rolle procedure, and more at right angles for the Kusnetz technique, the density of contour lines is lower in the latter, resulting in a lower error. An inherent error of ±9% is estimated for Kusnetz and ±13% for Rolle. The latter was estimated as ±20% in (44), but the contours have been shifted to the left in Fig. 4, thereby lowering the inherent error. This is equivalent to changing K from 203, the value chosen by Rolle, to 213 (46a).

The difference in the estimated errors for the two analyses derives essentially from the range of radon-daughter ratios that are assumed likely to occur in the mine atmosphere. Holub's errors in effect, are calculated from his most probable experimental mixture, RaA = 293 pCi, RaB = 97 pCi and RaC = 66 pCi; he considers the range of compositions in two dimensions. Rolle's analysis depends on a boundary given by two theoretical curves; his uncertainties are condensed into one dimension. His analysis places more weight on young air and this can be seen from Holub's graphs in Fig. 4 and 5, where the error is lower for young air using the Rolle count than for the Kusnetz count. Borak et al. (44) did not resolve a minimum error at low T_w (1-4 min), but in recent unpublished work such a "window", corresponding to that calculated by Coté et al. (58), Fig. 2, has in fact been observed using two-dimensional analysis. This lowers the inherent error on the Rolle method to ±8% (46a). An attempt to summarize the overall errors in Kusnetz and Rolle counts is shown in Table 3 (4).

Evidently, some further work remains to be done in this area but at this stage, we can conclude that, because of the convenience of its early count and its comparable accuracy, the Rolle procedure is preferable to the Kusnetz procedure for use in mines even when radon daughters alone are present in the atmosphere.

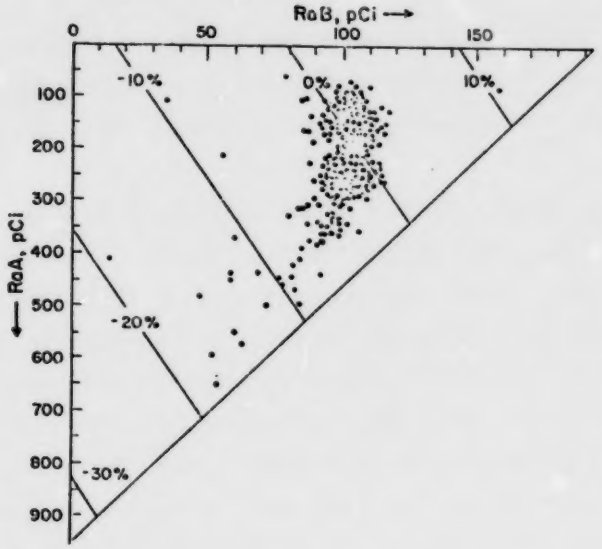

Fig. 5 - Errors for Kusnetz technique $T_s = 5$, $T_w = 40$, $T_c = 5$ min

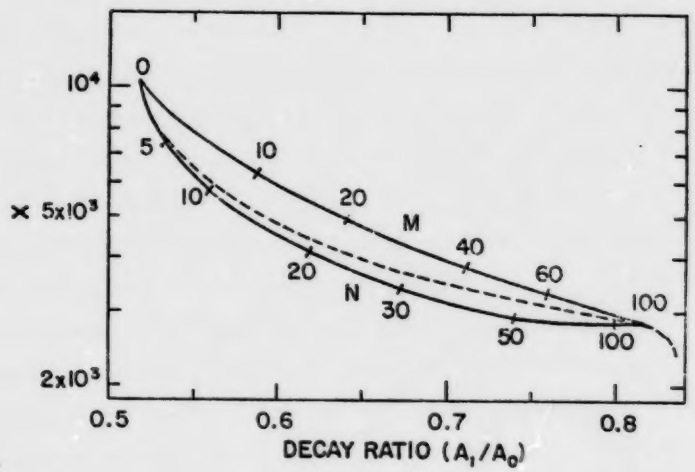

Fig. 6 - Function, X, versus decay ratio, Hill method. The numbers on N represent the age of the air in minutes while those on M are the values of 100 x N_B/N_A and 100 x N_C/N_A

The Holub diagrams provide a convenient visual display of the errors in different monitoring procedures. This method of error analysis is likely to be more general than Rolle's method of error analysis. Rolle's analysis applies essentially to underground mines. Holub's method could be extended to different environments such as houses and open-cut uranium mines in Australia (Section 10.2.1.2).

For example, recently, Jackson has made systematic radon-daughter measurements in houses in the USA (47,47a). The distribution of radon daughter ratios found is much more extensive than the 385 mine data points used by Holub. Jackson's data could be used to optimise all the one and two count procedures, described in this report for houses. In Australia, the Rolle count procedure is used extensively in open-pit uranium mines. Currently, in the Australian Radiation Laboratory, the Rolle procedure is being optimised by using a distribution of experimental radon-daughter ratios characteristic of open-cut uranium mines.

A debate is shortly to appear in Health Physics between those who prefer to plot radon-daughter ratios (Fig. 1) (47b) and the proponents of diagrams such as Fig. 3 (47c). In our view both types of diagrams serve a useful purpose. One advantage of the Holub diagram is that it is a linear plot; plotting ratios as in Fig. 1 gives a non-linear plot and leads to higher density of possible mixtures in certain locations of the radon-daughter map. We believe that criticism of the Holub diagram often results from lack of familiarity, in part stemming from insufficient exposition in the original papers. Superposition on the error contours of experimental points as done in this report does appear to aid interpretation. Given our description above and a little time, it should not be difficult to understand and use the Holub diagrams.

6.1.3 Two-count methods

These methods use an empirically obtained function of the ratio of the two counts. The magnitude of the function determined for a particular count ratio when multiplied by the first count gives the estimated working level, EWL. A two-count method can be viewed as a modified Kusnetz method: the Kusnetz factor being modified by the second measurement.

6.1.3.1 *Hill method*

The Hill method samples air for 2 min at 2 L/min, waits for 1.05 min, counts total alpha for 2 min (A_0 counts), waits 1 min and counts total alpha for 2 min (A_1 counts) (48). The ratio of A_1 to A_0 is then used to obtain the value of a function (X) from a supplied graph or table and EWL is calculated from:

$$EWL = \frac{A_o}{X} \cdot \frac{1}{\epsilon} \qquad \text{(iii)}$$

where ϵ is the average efficiency of the detector for RaA and RaC' alphas. An instant working level meter (IWLM) has been described (48).

Johnson took all possible daughter ratios between curves M and N, Fig. 1, (similar to Rolle analysis) and then calculated the decay ratios (49). Knowing the true working level for these compositions, TWL, he evaluated an upper and lower limit on the value of the function X as a function of the decay ratio, using equation (iii) with EWL replaced by TWL. A plot of X against decay ratio, dashed line, and envelope of values for the Hill method is shown in Fig. 6.

Holub has pointed out that, for any method, graphic interpolation is made with some error (46). He prefers to derive coefficients that together with counts I_0 and I_1 can be used to calculate WL. He calculates these coefficients using a linear or a parabolic approximation for the RaB concentration. He also calculates an inherent-error map and derives parameters for the estimation of individual radon daughters (equations for this purpose in (48) are in error). In addition, Holub gives inherent-error maps for individual radon daughters.

The statistical counting error is more significant than the inherent error in the Hill method. As the WL decreases, the counts are correspondingly lower and the statistical error higher. An attempt to summarize the overall error is shown in Table 3 (4).

In the CANMET laboratory, the Hill technique has been optimized by increasing the sample time to 5 min, at 5 L/min and by redrawing curve X as an average of the upper and lower limits; this reduces both the statistical and inherent errors.

6.1.3.2 *James and Strong (J-S) method*

This method differs from Hill's in that the first alpha count is taken during sampling and more than one sampling/counting scheme can be used. The procedure is to sample air at 10 L/min while counting alpha activity being collected on the filter (I_o) for 2, 5 or 10 min, wait 1 min and recount for the same length of time as that used for sampling (I_1). An automated apparatus, using this technique and a silicon surface-barrier type detector has been described (50).

Holub has derived optimized parameters for this technique and gives an inherent-error map and estimated overall errors in Table 3 (45).

He finds that changing the sampling and counting times changes the inherent error only slightly. He derives parameters for estimating individual daughter concentrations but does not recommend the James and Strong technique for this particular purpose.

6.1.3.3 *Shreve method*

This method employs an alpha and beta counter and uses the sum of net ($\alpha + \beta$) counts (the background of the counters is taken during sampling) (51). This sum has been shown to be approximately proportional to the WL for the time after sampling that is used. A 2-min sampling at 2.5 L/min, a 0.5-min waiting time, and a 1-min count (MDA1), or a 4.5 min waiting time and a 1 min count (MDA2) is used. This technique has led to a commercial instrument manufactured by MDA Scientific Inc. which gives direct reading of WL and also permits estimates of external gamma radiation present at the uranium mine site and radon concentration (52,53)*.

Holub has derived optimized parameters for the Shreve method; he uses separate parameters for alpha and beta conversion (45).

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* No recommendation is implied when commercial instruments are mentioned in the text. Conversely, any failure to mention an instrument of a particular company is not intended to signify lack of confidence in that particular instrument. A separate index of some commercial instruments has been prepared and is available from the NEA.

Overall errors are estimated in Table 3. Holub finds the inherent error better for the early count time. His conclusions are that for the Shreve method the inherent and statistical errors are almost a factor of three better than for the other two-count methods. Further recent work, where counting efficiencies for betas from RaB and RaC are not assumed equal, has led to substantial diminution of the inherent error (46a). Holub has investigated a combination of James-Strong and Shreve methods, with a sampling time T_s = 2 min, and with both alpha and beta counts made simultaneously. This gave the best characteristics of all two-count methods with the added bonus that the measurement is completed in 2 min. The method is indicated as HBS in Tables 3 and 4.

Holub has suggested that this method might be used effectively in a commercial apparatus (45).

6.1.3.4 *3R-WL method*

This method samples air at 2.5 L/min for 2 min, while simultaneously counting RaA and RaC' alphas separately. It then uses the function:

$WL = (5I_a + 20I_c,)/10^5$, where I_a and I_c, are the counts from RaA and RaC', respectively. An IWLM has been described (54).

Energy discrimination (two-count alpha-spectroscopy) does not produce any improvement in inherent error as shown in Table 3. However, this technique has recently been optimized for use in houses (54a). Also, analysis of this technique with wait times of 25 min indicates a substantial lowering of the inherent error (46a). The method should be distinguished from alpha-spectroscopy in which three counts are recorded: 1 count in the RaA channel, and 2 counts separated by a time interval in the second RaC' channel. The latter is an "exact" method and is discussed below. A summary of one- and two-count methods is shown in Table 4 (4).

6.1.4 Three-count methods

These are "exact" methods which completely determine RaA, RaB and RaC, hence WL. Besides methods utilizing 3 counts of gross alpha there are alpha-spectroscopic techniques including measurement of alpha and beta emission.

The three-total-alpha count Tsivoglou method has been optimized by Thomas (55): he recommends 5 min air sampling followed by alpha counts from

Table 4 - Grab sampling methods for determining airborne radon daughter concentrations (taken from reference (4))

Method and reference	Sampling Time (min)	Flow rate (L/min)	Analytical procedure[a]	Total Time (min)
1) Kusnetz 5-40-2 (42)	5	2	Allow sample to decay for 40 min; count gross alpha (A) for 2 min: WL = A/(20 x 150)	47
2) Kusnetz 5-90-2 (42)	5	2	Allow sample to decay for 90 min; count gross alpha (A) for 2 min: WL = A/(20 x 60)	97
3) Rolle (43)	10	2	Allow sample to decay for 4.4 min; count gross alpha (A) for 2 min: WL = A/21300	19.4
4) Shreve (52)	2	2.5	Allow sample to decay for 0.5 min; simultaneously count alpha (A) and beta (B) for 1 min: WL = (A + B)/4400	3.5
5) Shreve corrected (53)	2	2.5	Same as 4 WL = C x (A + B)/4400 C is a correction factor based on the alpha/beta ratio	3.5
6) Shreve optimized (45)	2	2.5	Same as 4 WL = (A/6330) + (B/3080)	3.5
7) Hill alpha ratio (48)	2	2	Allow sample to decay for 0.5 min; count gross alpha for 2 min (A_1); allow additional decay for 1 min; count gross alpha for 2 min (A_2): WL = Kx (A1/A2)	7.5
8) Hill optimized (45)	2	2	Same as 7) WL = (A_2/1340) - (A_1/4065)	7.5

Table 4 (Cont'd)

Method and reference	Sampling Time (min)	Flow rate (L/min)	Analytical procedure[a]	Total Time (min)
9) James and Strong (50) alpha ratio	5	10	Count gross alpha during 5 min sampling interval (A_1); decay for 1 min; count gross alpha for 5 min (A_2): $WL = K (\frac{A_2}{A_1})$	11
10) James and Strong (50) optimized	5	10	Same as 9 $WL = (A_2 - A_1)/5450$	11
11) HBS (45)	5	10	Simultaneously count alpha (A) and beta (B) while sampling: $WL = (A/32400) + (B/11700)$	2
12) 2-count alpha spectroscopy (54)	2	2.5	Simultaneously count A_A and $A_{C'}$ while sampling: $WL = (5 A_A + 20 A_{C'})/100000$	2

a - A = gross alpha disintegrations
B = gross beta disintegrations
A_1 = disintegrations during first alpha count
A_2 = disintegrations during second alpha count
A_A = Po-218 (RaA) disintegrations
$A_{C'}$ = Po-214 (RaC') disintegrations

2 to 5, 6 to 20 and 21 to 30 min. He derives equations, involving the three counts, the sampling flow rate and known numerical constants, to give the concentration of each of the radon daughters. Simple equations giving the standard deviation of the daughter concentrations have also been derived.

Groer proposed a method in which alpha particles from RaA and RaC' are resolved during the counting period and at the same time the activity from RaB and RaC is measured by detecting the beta particles that pass through the back of the filter (56). The beta contribution from RaC is inferred from its alpha activity and the RaB activity obtained by difference. A sophisticated IWLM has been constructed, the Harshaw Environmental WL meter. The main limitations of this device are its size and power consumption, making it impractical as a portable monitor.

Alpha-spectroscopic techniques, in which one count of RaA is made in one channel at 6.0 MeV and two counts of RaC' are made in a second channel at 7.7 MeV, have been reported (57,57a,57b,58,59). Martz et al. (57) estimate radon daughter concentrations from one alpha count rate of RaA and two alpha rates of RaC' at 5 min and 5 min and 30 min, respectively, after collection of the air sample. Kerr (57a) has written a computer program to optimise the procedure for one integral count of RaA and two integral counts of RaC'. Tremblay et al. used the same error propagation methods employed by Kerr, to optimise a two channel integrated count method for counting during and/or after sampling (59). In Kerr's method 3 errors are propagated in the equations: statistical error, flow rate error and error in geometric factor. In the second channel, it is advantageous to count as early as possible, when mostly RaC' from RaC on the filter is counted, and as late as possible when primarily RaC' from RaA and RaB on the filter is counted. Counts for times in between lead in the equations to subtraction between pairs of large quantities with substantial errors in the small quantities evaluated. A balance must be struck between separation of the 2 counts and the concomitant increase in statistical error with decreasing count period.

Alpha spectrometric methods have the advantage of more precise estimation of RaA concentrations. This is particularly so for methods that count during sampling.

Holub has described a technique, in which 1 count of alpha and 1 count of beta are made simultaneously, followed by either a second beta count or a second alpha count - a Shreve-Tsivoglou procedure (45).

6.2 Grab-sampling of Mixtures of Radon and Thoron Daughters

A number of workers have considered the measurement and evaluation of the health hazard of thoron daughters in the atmosphere (58.60,61,62,63, 64). Rock measured thoron-daughter WL of about one half those of radon-daughter WL in a mine in Alaska (64). He measured thoron daughters by a single count, 5 h after sampling, after most radon daughter activity had ceased. Similar relative WL concentrations between radon and thoron daughters have been found in Canada (58) and in Norway (61).

Coté and Townsend, taking into account the concentrations of U_3O_8 and ThO_2 in the ore, estimated the relative rate of diffusion of radon and thoron from rock and plotted Tn(WL)/Rn(WL) as a function of age of air in the mine (58). Their results agreed qualitatively with experimental observation. More interestingly, they indicated that relative radon to thoron WL might serve as an additional indicator of ventilation conditions, just as relative radon daughter concentrations have previously been used. Ventilation is more effective for control of radon gas, having a half life of 3.82 days, than for control of thoron gas which has a half life of 54.5 s. On the other hand, ThB, having a half life of 10.6 h, is more effectively controlled by ventilation than radon-daughter activity because of the relatively short half lives - 3.05, 26.8 and 19.7 min, respectively, for RaA, RaB and RaC. One air change every 10 min limits thoron daughter potential alpha energy to about 1% of its maximum while the same ventilation rate limits potential alpha energy from radon daughters to about 18% of its maximum (65). Control by ventilation is discussed in (7,8).

Coté and Townsend noted that the Kusnetz factors of radon and thoron daughters had a different time dependence and that at a certain time after sampling they were equal. They derived a two- or three-count total-alpha method suitable for any atmospheric mixture of radon and thoron daughters (58). An early count at 1.2 to 16.2 min after sampling, when thoron daughter counts are negligible, gave Rn(WL); a count at 165 to 180 min gave a 'total WL': K, the Kusnetz factor, is approximately the same here for radon and thoron daughters, i.e., K(Tn) and K(Rn) intersect at this waiting time. Tn(WL) was obtained by subtraction of Rn(WL) from the 'total WL'. Two counts alone would suffice but a third 'redundant' count can be made at 225 to 240 min to measure Tn(WL) thereby lowering the overall error. At this time RaC' counts are not significant and K is independent of age of air, Fig. 7. This

was shown by plotting K as a function of time, after sampling, for air of age 500 min and for air of age 1 min. At approximately 230 min the two curves intersect.

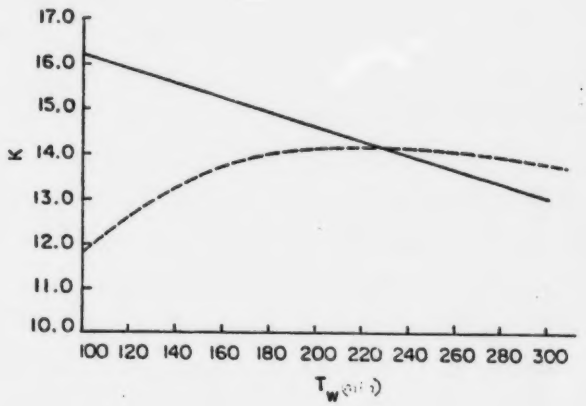

Fig. 7 - K versus waiting time T_w for thoron daughters: full line, mine air of age 500 min; dotted line air of age 1 min

The times of counting given above depend on the duration of sampling and counting. They are given as examples and not intended as recommendations. Individual laboratories should decide on convenient duration times for sampling and counting and optimise the waiting times with a reliable computer program - the CANMET program is available.

Coté and Townsend calculated errors in WL(Rn) for standard radon daughter counting procedures when all alpha counts from a radon and thoron daughter mixture were attributed to radon daughters (58). Providing overall counting times are short, $\leq$30 min, these errors are small. Rn(WL) is overestimated when thoron daughter concentrations are ignored in these mixtures, a frequent practice until recently in Canadian mines. A 40-min Kusnetz count

overestimates Rn(WL) by 28% if Tn(WL) = Rn(WL). Failure to take thoron daughter concentrations into account can, however, result in a significant underestimation of the dose. Evidently, the Rolle count is preferable under these conditions.

Coté and Townsend also optimized a three-channel alpha-spectroscopic scheme using a counting time of $\geq$30 min (58). In the first channel, a count at 6.0 MeV measures RaA and ThC; in the second channel two counts at 7.7 MeV separated by a time interval measure RaC'; in the third channel two counts at 8.8 MeV measure ThC'. In the first energy channel the alpha counts from ThC are equal to 56% of the alpha counts from ThC' in the third channel. Five unknowns, RaA, RaB, RaC, ThB and ThC are calculated from the five counts by computer. A certain overlap of the RaC' and RaA counts (8%) occurred in the first channel and of the ThC' and RaC' counts (12%) in the second channel due to energy degradation of the α-particles. The energy degradation is a function of the type of filter paper used, particle size, sampling flow rate and geometric factors. It must be determined for each experimental system. The overlaps are taken into account in the computer program.

A small ruggedized portable three-channel alpha-spectrometer, Canalph-3-Pylon instrument, has been developed in the CANMET laboratory (66) from a two-channel design of Keefe (67). It employs a diffused junction, silicon detector with discriminators and is controlled by a microprocessor. The Coté-Townsend three-gross-alpha count, the Hill, Thomas, Rolle and the alpha-spectrometric technique, described above have been programmed into the instrument. WL and daughter concentrations are automatically displayed on the instrument manufactured by Pylon Ltd. Alphanuclear, Eberline and EDA also market a portable microprocessor controlled IWLM. Purdue (68) has reported an alpha-spectrometric technique for counting radon and thoron daughters.

6.3 Continuous Radon Daughter Measurement

Monitoring systems are being developed to measure continuously radon daughter concentrations in air: a detector is placed in a particular location in the mine and sampling and counting proceeds uninterruptedly. These systems can, in principle, eliminate the uncertainty in measured exposure levels from fluctuation in the radon daughter concentration between periodic grab-sample measurements. Continuous WL monitors can be applied to control radiation exposure in mines, in ore processing mills and at mill tailing sites. The

method can also be used to calibrate personal dosimeters designed to measure WL over extended periods.

Haider and Jacobi reported a continuous alpha-monitoring device employing a diode-type alpha detector (70). Holmgren used a commercial air-particulate monitor and measured the beta activity of RaB + RaC (71). Kawaji has described a technique using a proportional counter detector (72).

A U.S. Bureau of Mines investigation has evaluated the feasibility of gross-alpha and beta counting as a means of continuous measurement of WL (26). For beta detection a Geiger-Muller tube and a large 47-mm filter holder was used. The problem of plate-out was avoided in the beta method by detecting the beta particles from the backside of the collection filter. In the alpha method particulates were collected on a 25-mm filter holder, which was located about 50 mm from the detector, a surface-barrier type diode with an area of 300 mm^2. The beta detector also responds to gamma rays; this background activity was subtracted from the gross activity. Inherent-error studies indicated that 90% of experimental points were between the ±3% contours for the gross-alpha method, and between the ±8% contours for the beta method, Fig. 8. However, the beta method was found more useful because it avoids problems with plate-out of unattached radon daughters on the surfaces of air openings leading to the filters. The count rate from a continuous beta monitor followed ambient radon concentration at about a 15-min time resolution as shown in Fig. 9.

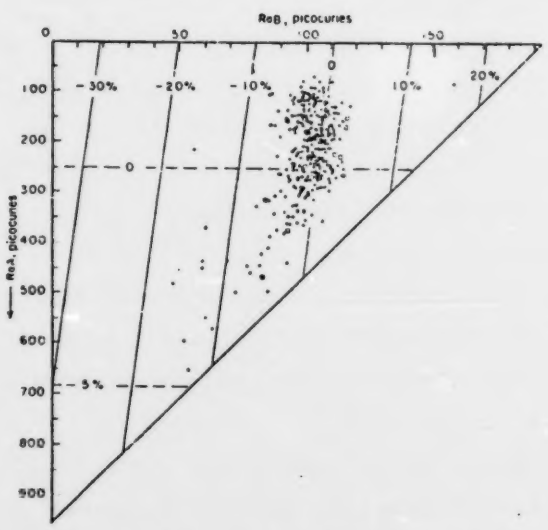

Fig. 8 - Distribution of RaA, RaB and RaC in mine atmospheres and the inherent error for gross-alpha - (dashed line) and gross-beta - (full line) measurements

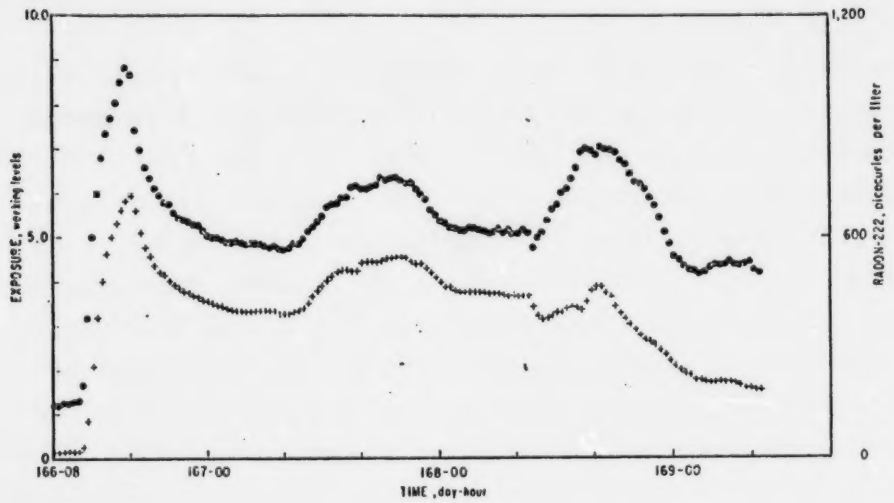

Fig. 9 - Working level, measured with beta detector (+ marks) and radon levels (solid circles) for 72-h period in the Twilight Mine

After detectors had been initially switched on or moved, a minimum 3-h sampling time was required before count rates could be related to WL since calibration depended on the assumption that radon daughter equilibrium was established on the filter paper.

Problems were experienced with filter papers (26,72): a membrane-type filter provided the least amount of α-particle energy degradation but it became clogged in a few hours at a flow rate of 1.0 L/min in a typical underground mine atmosphere. A fibreglass filter did not show this severe clogging problem but there were changes in self-absorption characteristics of a particle when relative humidity fluctuated.

A comparison of characteristics and uncertainty parameters for several continuous radon daughter monitors is shown in Table 5 (4). Droullard has recently reviewed instrumentation for continuous radon daughter measurement and for personal dosimetry (39).

The most attractive design concept for a continuous monitor is one in which several detectors are multiplexed into a central control unit at a location that can readily be observed by mining staff. In a system at the

Table 5 - Characteristics and uncertainty parameters for several continuous radon daughter monitors (taken from reference (4))

Activity measured	Detector	Efficiency (%)	Flow rate (L/min)	Counting time (min)[a]	U(A) (%)	U(P)[b] (%)	U (%)	Reference
Alpha	Surface barrier	20	1-10	15	2.1	0.7	2.2	(26)
Beta	Geiger Mueller	12	1-10	15	8.0	0.7	8.1	(26)
Alpha	Proportional Counter	20	1	15	3.5	0.7	3.6	(72)

a - The integrating time is selectable. Tests performed by the U.S. Bureau of Mines used counting times of about 40 min.

b - Precision is based on sampling air at 1 L/min for 15 min when the potential alpha energy is equivalent to 1 WL.

U.S. Bureau of Mines, 32 detectors can be serviced (73). Each detector station is in turn connected by a cable to a central underground transmitter unit which is connected to a surface control unit. Here, signals are analyzed and appropriate alarms and indicators are controlled. The system is programmed to sound an alarm at a preset concentration between .01 and .99 WL. If the concentration exceeds 1.0 WL an alarm is also sounded underground. It is estimated that the cost of such a system comprising 32 detectors would be $90 000, not including installation (4).

Although continuous monitors avoid the uncertainty due to fluctuation in the radon daughter concentration between periodic grab samples, an uncertainty, U(O), remains from the occupancy factor for the individual miner.

6.4 Personal Dosimetry of Radon and Thoron Daughters

Personal dosimetry avoids the primary source of uncertainty involved in grab sampling, i.e., fluctuation in WL concentrations. Cumulative exposures are recorded automatically regardless of fluctuations. Uncertainties from occupancy time, which are relevant in grab sampling or area monitoring, are eliminated in this technique.

A personal dosimetry system must function reliably under severe mining conditions at an economically reasonable cost. The size, weight and placement of the dosimeter on the miner's person i.e., hat, chest or belt, are factors which must be considered in deciding whether a dosimeter is suitable for underground operations.

Many different types of personal dosimeters for radon and thoron daughters, both active (74,75,76,77,78,79) and passive (80,81), have been proposed. Several have been tested in active uranium mines; two are in routine use underground (76,81).

Active dosimeters are those in which a known volume of air is pumped through a filter by a battery-driven pump. Alpha particles emitted by radon daughters deposited on the filter are recorded by a detector, which can be either a TLD chip, a track-etch film or an electronic solid-state silicon detector.

6.4.1 Active personal dosimeters

Some of the key parameters in an active dosimeter include (82): volume of air pumped and constancy of air flow; effects of plate-out of unattached daughters on surfaces; self absorption of filters; sensitivity of filter and detector to humidity and dust loading; mechanical reliability and integrity of pumps, valves, turbines, filters, detectors and housings; electrical reliability of motors, batteries and chargers; sensitivity of pump to physical orientation or positioning; efficiency (geometry of the detector in relation to the source); reliability of processing and read-out mechanism for each detector type; approximation of air sampled to breathing zone of wearer; knowing what radionuclides are being sampled, i.e., RaA, RaC', ThC or ThC'; interference of gamma radiation or other types of background.

Each of these parameters has an associated uncertainty; a proper design of dosimeter is required to minimize this uncertainty so that each measurement of the worker's personal exposure is the most accurate available (82). Thus, the requirements for a reliable active personal dosimeter are rather stringent. As yet, no one dosimeter fully meets these specifications, even though some are in routine use.

6.4.1.1 *CEA dosimeter*

The most advanced dosimeter is one developed over the past 10 years by the CEA in France (76). This dosimeter is a compact, light-weight package designed to be worn on the belt of the miner. A turbine pump forces air via three small inlet holes at the base of the dosimeter head through a Millipore filter at about 100 mL/min.

Three collimators select the different alpha particles emitted in a direction perpendicular to the front face of the filter. On the opposite side of the collimators, a thin Kodak Pathe LR 115 film serves as a track-etch detector. Different absorbers in each collimator ensure that alpha particles from ThC', RaC' and from RaA and ThC are registered in three distinct zones of the film. Filters are retained in the dosimeter for 1 month or less after which exposed films are removed from the dosimeters and etched in controlled laboratory conditions in 2.5N NaOH solution at 60°C for 90 min. Tracks may be counted under a microscope or automatically by image analyser, colony counter or spark counter. Working levels are derived from:

$$WL(Rn) = \frac{7.7\ N_2 + 6.0(N_1 - 0.56\ N_3)}{1.3 \times 10^5\ \epsilon \times V}$$

$$WL(Tn) = \frac{8.8\ N_3 + 6.0(0.56\ N_3)}{1.3 \times 10^5\ \epsilon \times V}$$

where N_1 is the number of tracks in the RaA zone; N_2 the number of tracks in the RaC' zone and N_3 the number of tracks in the ThC' zone, ϵ is the efficiency and V the volume of air sampled.

A reasonable agreement has been reported (76) between the average counts recorded with the CEA dosimeters and those recorded for the same time period using grab sampling techniques of Rolle, Thomas and MDA. However, some problems remain with the CEA dosimeter: a turbine pump does not regulate flow rate; dust and moisture affect the filter's resistance. Examination of the dosimeters in normal mining conditions at Elliot Lake, Canada, has indicated variation in flow rate from ±15% to ±10% (83). Phillips et al., working on a contract from EMR noted that under extreme conditions of soaking wet filter the dosimeter failed (84).

A major fault was observed recently in tests conducted by EMR for the Atomic Energy Control Board of Canada (AECB) in normal mining conditions at Elliot Lake (83): of 25 dosimeters tested, the films of 9 showed marked contamination (85). This consists of intense groups of tracks concentrated near the edges of the exposed areas as shown in Fig. 10. Contamination arises from radioactive dust lodged close to the film.

Where these dosimeters are in current use, absorbers are now changed monthly to minimize contamination (86). To eliminate the problem Tremblay proposes the addition of two 'O' rings to the CEA dosimeter: one between the cover and the main body to intercept any possible flow of contamination through the threads of the cover; a second between the main body and the collimator block below the position of the attenuators (87). The addition of the second 'O' ring will necessitate the lowering of the upper part of the alignment groove. He also proposes the addition of a disc of thin mylar to seal the lower end of the collimators. Some modifications are being made to the CEA dosimeter (86).

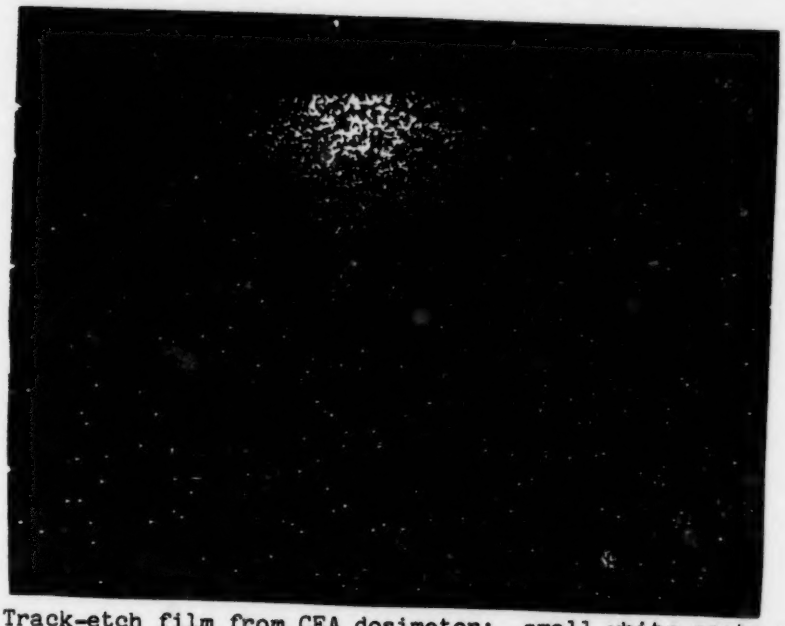

Fig. 10 - Track-etch film from CEA dosimeter: small white spots are tracks, large conglomeration, centre top, is contamination

The CEA system has been adopted for radiation protection in underground mines in France. The annual cost, including acquisition of the dosimeter (3-year depreciation), maintenance, and laboratory to process the film, is $444 U.S. (in 1980) per miner (88).

6.4.1.2 *Alpha nuclear electronic personal dosimeter*

This instrument is based on a prototype developed at the U.S. Bureau of Mines. The dosimeter is a compact, rugged, lightweight unit consisting of a silicon solid-state detector, electronics and an internal, constant-flow pump drawing air through a 25-mm filter at 50 mL/min (89). Total-alpha counts are stored within the memory. The dosimeter is used in conjunction with an aboveground reading network. The microprocessor controlled version of the reader directs all modes of operation for the dosimeter. The dosimeter fits the standard miner's cap lamp battery and is worn throughout the entire shift. After this counting period, the unit is connected to the reading network where the day's data are dumped, calculated and stored. A thoron total-alpha count can readily be programmed into the system to take effect at the end of the shift. An advantage of this dosimeter is that a reading may be obtained

immediately on completion of a work period. Evidently, this is a much more sophisticated and sensitive instrument than the CEA dosimeter. Preliminary tests underground indicate satisfactory performance (90). However, extensive tests have yet to be conducted to ascertain its reliability for routine use in underground mines. Detailed experiments are required, for example, to examine its possible susceptibility to intermittent shock and contamination. The latter could conceivably be a general problem with personal dosimeters.

A pilot scheme, initiated by the AECB in which 10% of miners carry either the CEA or the Alpha nuclear personal dosimeter is now beginning in Canada. Experience gained here is likely to answer many of the outstanding questions concerning these dosimeters.

6.4.1.3 *Active TLD dosimeters*

Personal dosimeters utilizing thermoluminescent detectors have been described by a number of groups (74,77,78,79,80,91).

A small crystal of LiF or CaF_2 is located near the front surface of the filter in the dosimeter. Defects are produced in the crystal by alpha emission from the filter. Light is emitted from the defects when the crystal is heated under controlled conditions. The light intensity is proportional to the number of defects formed, hence to the number of alpha-counts from the filter. Gamma background is monitored by a second crystal shielded from the radioactivity on the filter. Small portable pumps with servo-regulated flow rates were used in the dosimeter system developed by the U.S. Bureau of Mines.

Results of tests carried out by Southwest Research Institute for the U.S. Bureau of Mines were not encouraging (92). Pump performance was poor and excessive filter loading and clogging of air passages were experienced.

An active sampling device, which employs a small filter and thermoluminescence detectors with low gamma-sensitivity, has been used as part of an integrating personal or area monitor (93). The lower level of detection of 0.005 WLM (sampling time: 170 h) can be achieved with a flow rate of 100 $L.h^{-1}$.

Grealey et al have described a dosimeter that uses $CaSO_4$: D_y TLD material in teflon as detector (94). This instrument has been field tested in underground and open-cut uranium mines in Australia and found stable in adverse climatic conditions. A sensitivity is claimed of 0.03 WLM for radon daughters and 0.04 WLM for thoron daughters at a flow rate of 30 $L.h^{-1}$ (sampling time: 170 h).

6.4.2 Passive personal dosimeters

Passive dosimeters rely on the natural migration of radon and attached and unattached radon daughters to the sensitive area of the detector; track-etch detectors are used. Several systems have been described (80,81).

Domanski protects the detector, cellulose nitrate or cellulose triacetate film, by a wire screen which allows suspended radon daughters to pass through (81). The device is attached to the rear of a miner's cap and is able to withstand mining activity for extended periods. This device has been used in Poland for several years and offers advantages such as maintenance-free operation (due to the overall simplicity, lack of moving parts and lack of sophisticated electronics) and low operating costs - ~$180 per year. However, there are some difficulties: the calibration factor converting track density to potential alpha energy is very sensitive to the equilibrium factor between radon gas and radon daughters. This aspect is under study (81). In the version of the differentiating track detector, 2 or 3 films together with aluminium absorber foils, are part of a helmet cassette. The equilibrium factor is assessed from the ratio of the surface track density on the uncovered film as compared with the density on the covered film (95).

A passive integrating radon monitor for environmental monitoring using a track-etch α-particle detector has been described by Alter and Fleischer (34). This device has been adapted for use as a personal dosimeter for miners (Terradex). Its use in monitoring radon daughter levels relies on a knowledge of the equilibrium factor between radon and its daughters. Only if this factor were to be reasonably constant within certain working areas could this device provide a simple method of monitoring WL. However, in this method, the occupancy factor for the miner would also need to be monitored. More experiments are required to examine the variation of equilibrium factors in different working areas.

Research in passive personal dosimeters is likely to progress with development by Tommasino of electro-chemical etching techniques, and thick, sensitive films, and with the possibility of high resolution alpha-spectroscopy in CR39 films (97).

6.4.3 Requirement for automatic readout of track-etch films

Automatic readout of track-etch films is desirable but not yet generally implemented. A commercial, colony counter may be satisfactory (98). Piesch finds the method best, in the 5 cm^2 field, for total track counts from about 20 to 500 (33). Image analysis offers a powerful but expensive alternative. Counting by successive discharge of a spark is fast, reasonably accurate and inexpensive (98). A semi-automatic machine has been designed in the CANMET laboratory and has been built by Bondar-Clegg Ltd. Strippable Kodak LR 115 Type 2 film is used. The film must be cut cleanly before use facilitating stripping of the plastic backing after etching. Electrochemical etching and use of thick films is a promising domain to be explored in the future (97,33).

7. UNATTACHED FRACTION AND PLATEOUT OF RADON DAUGHTERS

In the control and monitoring of airborne radioactivity in mine air or other atmospheres, it is important that a proper and detailed understanding exists of the mechanisms of transport and the ultimate fate of radon and its daughters. Central to this is the complex partitioning of the daughter activities into what are generally considered as three distinct states:

a) as molecular-sized clusters in the free or unattached state,
b) in the aerosol attached state, or
c) deposited on surfaces (walls, equipment, clothing etc).

7.1 Unattached fraction

Although RaA starts its life as a positively charged atom, it usually soon attaches to an aerosol particle in the air. When RaA decays, the newly formed RaB atom may recoil off the aerosol particle and hence start its life as an unattached atom. Some RaA (and RaB) atoms may never attach and consequently there is a certain probability of finding all daughter products in the unattached state. The nature of unattached particles may depend on the atmosphere i.e., on trace gases. However, a common diffusion coefficient has generally been assumed for all unattached clusters. This value is approximately 2 orders of magnitude greater than that for attached particles.

Recently, the exact nature of free or unattached radon daughters has been receiving close attention. In the papers of Busigin et al. (99) and also of Frey et al. (100) the validity of a unique diffusion coefficient appropriate to free Po-218(RaA) is questioned. The important influence on diffusion coefficients arising from trace gases and organic vapour is highlighted. Busigin et al. suggest that unattached RaA consists of a number of different entities with different diffusion coefficients. They also suggest that the experimental conditions of earlier workers may have led to measurement of a diffusion coefficient for the most mobile type (99) (see below in 7.2).

From a radiological point of view only the airborne fraction of the daughter products is of interest. The magnitude of the total airborne fraction as well as the distribution between attached and unattached daughter products, may differ widely from one situation to another. Because of their higher diffusion coefficients unattached daughers, when inhaled, tend to be retained, by plateout, in the upper part of the respiratory tract, especially in the bronchii, which are considered to be the most likely site for tumours to develop. According to several dose models, the doses delivered from equal concentrations of unattached and attached RaA and RaB may be in the ratio 1:2. It is therefore of interest to know the concentration of unattached daughter products.

The concentrations of unattached radon daughters are usually measured by passing the air through a fine-meshed net (101). The attached particles pass almost unhindered through the net and can be collected on a backing filter. On the other hand, the unattached particles deposit to a large extent on the net because of their high diffusivity. The resulting activity on the net is then counted. The collection efficiency of the nets can be calculated theoretically if the diffusion coefficient of the particles to be collected and the geometry of the net is known.

For situations where these conditions are not met, the following three-net-method has been suggested. The air to be examined is pumped through a filter in front of which is placed three identical nets. As the air passes through the nets and the filter, part of the activity, mostly unattached daughters, deposits on the nets. The rest, mostly attached daughters, deposits on the filter. The activities on the nets and filter are counted simultaneously after sampling. In principle it is possible to deduce from these activities the unattached fraction of each individual daughter and the

efficiencies of the nets for collection of unattached and attached daughter products (102,103).

Unattached fractions have also been measured, in Australian mines, using either a diffusion battery or a diffusion impactor (103a). A critique of methods of measuring unattached fraction has recently been published by van der Vooren et al. (104). They examined methods using parallel plate, inertial impactor and wire-screen devices. They concluded that substantial errors were likely to occur in these methods and that published values of unattached fractions measured in the environment should be interpreted with care.

7.2 Plateout

The removal of airborne radon daughters in either the free or attached states by deposition onto surfaces is now generally called plateout. Problems due to plateout may arise both in the design and use of personal and area monitoring equipment. Plateout also plays a significant role in the development of control techniques to reduce exposure due to airborne radon daughters. Without proper knowledge of plateout rates it is difficult to predict accurately the likely partitioning of radon daughters between the three possible states. Wicke and Porstendorfer have made measurements of plateout in German homes (105). Not unexpectedly, it was found that the working level ratio, i.e., the equilibrium factor (see Glossary for definition) increases at higher aerosol concentrations. This is because the radon daughters attach preferentially to the more available aerosol particles instead of being deposited by plateout onto surfaces. Jonassen and McLaughlin working on the effect of air filtration on radon daughter levels in a sealed room noted a similar effect. They also noted that at very low aerosol concentrations (1 to 5 x $10^2/cm^3$) the unattached fraction was so high that the major process of removal of ^{218}Po activity was plateout and not filtration (106). A study by George suggested that plateout was responsible for reducing indoor airborne radioactivity and caused lower than expected working level ratios when ventilation rates and radon sources indoors were taken into account (107).

Plateout-related phenomena were considered sufficiently important that the U.S. Bureau of Mines sponsored a working conference on the subject at the University of Illinois in 1979 (108). As a result of this and other

subsequent meetings it has become abundantly clear that until recently very few reliable experimental measurements were available of such fundamental properties as U^f and U^a, the plateout velocities of free and attached radon daughters respectively. In a cavity of volume V and surface area S the functions U^fS/V and U^aS/V are the plateout rate constants for free and attached daughter activities, respectively.

There are excellent models available, such as those of Jacobi (63) and Porstendorfer et al. (109), which can be used to calculate the behaviour of radon daughters in any air cavity. In these models U^a was estimated as 10^{-2} cm/sec or 10^{-3} cm/sec. For the free daughters U^f was estimated to range from 0.5 to 1.5 cm/sec and from 1 to 3 cm/sec. In experiments carried out at the Environmental Measurements Laboratory (EML), U.S. Department of Energy, New York, direct measurements were made of plateout activity on surfaces within a near cubical room with stainless steel walls (110). It was found that the values of U^f and U^a used in the Jacobi model substantially overestimated the amount of surface plateout activity and at the same time underestimated airborne activity levels. Further extensive measurements at EML have shown that the model constants used overestimate plateout and underestimate airborne activities by factors of about 3.5 and 3.3 respectively (111). As expected, they have also shown that the amount of plateout is strongly dependent on aerosol levels, varying from 4%, at particle concentrations $>10^5/cm^3$, to 86%, for particle concentrations $<10^3/cm^3$. Here plateout percentage is defined as WL (surface)/WL (air + surface).

By means of a linear programming technique the Jacobi room model was optimized to fit the experimental data on the partitioning of radon daughters between airborne and surface deposited states. The major change resulting from this has been to reduce U^f to 0.05 cm/sec. This new value of U^f strongly implies that the diffusion coefficient of free radon daughters is approximately 0.0025 cm^2/sec, which is a value much smaller than the frequently quoted value of 0.05 cm^2/sec. This "new" diffusion coefficient corresponds not to an atom but to an ultrafine aerosol particle of about 5 nm (50Å) in diameter. Busigin (99) and Frey's (100) work is of interest here.

It is important to note that the EML derived value of U^f = 0.05 cm^2/sec requires that the attachment rate to aerosols should also be reduced. Reducing this attachment rate was considered undesirable as it would increase

the predicted ratio, of free to attached daughters, to a value not in agreement with experimental evidence. This very important inconsistency has not yet been resolved. The conclusions of van der Vooren (104) may be of relevance here (see 7.1).

Scott recently has reported on investigations in Canadian houses where measured surface alpha activities suggest a U^f value of about 0.15 cm/sec (112). This is intermediate between the estimated Jacobi and the measured EML values. Scott also noted higher than average values of U^f for plateout on walls where a convectional air flow in the range 4 to 12 cm/sec was observed. It is suggested that turbulence in the convectional layer could be an effective deposition mechanism.

McLaughlin, in Ireland, has made measurements of plateout activity, by measuring directly the plateout of alpha emitting radon daughters onto the surface of a surface barrier detector, mounted within a 50 litre chamber filled with aerosol-free air (113). A mean value of U^f = 0.036 cm/sec has been obtained in these experiments, which is close to the EML values.

Plateout of radon daughters on detectors, or on surfaces within alpha particle range of detectors, may make the most significant contribution to the recorded alpha count in a wide range of passive "radon" detectors. McLaughlin has investigated the passive detection of radon and its alpha emitting daughters in a number of different cylindrical geometries using both the alpha track plastic CR-39 and a surface barrier detector to detect the alpha particles (113). These studies have shown, under maximum plateout conditions and in the case of near 2 π counting geometry, that approximately 65% of the recorded alpha signal arises from daughter activity plated out on the detector. The radon and the remaining airborne alpha emitters make a contribution of 35% in this case. For a detector mounted in the base of a cylinder of diameter 4 cm the plateout activity on or near the detector made an alpha count contribution greater than 80%.

Frank and Benton (114) have reported some plateout problems in passive radon dosimetry using a track-etch dosimeter. Fluctuations in response, differing by 15 to 20% were found with parallel detectors while counting statistics varied by only 3%. They suggested that this may be due to electrostatically enhanced plateout by charges trapped in the plastic. They also report fluctuations in the response of dosimeters mounted in various locations on manikins. They attribute these to probable plateout effects.

Where passive detectors are used, a contribution to the alpha signal arising from plateout activity is not in principle unacceptable. Problems really arise when the amount of plateout changes significantly during the exposure periods, due to changes in the state of the surrounding air, i.e., humidity, aerosol characteristics, air ionization rate, etc.

8. FIRST STAGES IN A PROGRAM OF RADON DAUGHTER MEASUREMENTS IN A MINE

Earlier sections in this report described in some detail methods of monitoring radiation. In part for reasons of conciseness, much background knowledge on the part of the reader was assumed.

For those workers completely new to the field the following attempts to give some guidance in the first stages of a measurements program.

The simplest method of measuring WL in a mine is the Kusnetz method (42). The basic method of measurement is described in detail in a Radiation Monitoring Training Manual 'Radiation Monitoring' published in July 1976 by the U.S. Department of the Interior, Mining Enforcement and Safety Administration, Technical Support, Health Technology Division, Denver, Colorado (69). This manual gives an excellent background of the radon-daughter field including an account of equipment selection and calibration, a description of errors, common problems encountered in determining radon-daughter concentrations and sampling patterns for measurements in mines. In Canada, guidelines for a standardized Kusnetz method have also been described by the AECB (41).

For counting by the Kusnetz method, one requires a battery operated pump for sampling air through a filter, at 2 litres/min during a shift period of 8-10 hrs, a scintillation detector and a rate meter or scaler. Guidelines for equipment selection are given in (69).

Radon daughter particulates are filtered from 10 litres of mine air in a period of exactly 5 mins (69). The alpha activity is counted between 40 and 90 mins after the end of sample with an appropriately calibrated instrument. Counts per min (cpm) are converted to actual decay events (dpm) occurring on the filter paper. Each counter is calibrated for gross counting efficiency of RaC' (7.7 MeV) alpha particles (after 40 mins, only alpha particles from the decay of RaC' are counted - 99.99% of RaA has decayed). Counts per min divided by gross counter efficiency gives the actual disintegrations per min. Charts or graphs are available to facilitate the conversion of meter reading (cpm) to disintegrations per min or to actual WL if sample volume is constant.

Disintegrations per min per litre of air are obtained by dividing disintegrations per min by the total litres of air filtered. Disintegrations per min per litre of air are converted to the multiple or fraction of a WL at the time of sampling by dividing by the appropriate time factor (Kusnetz factor, K). Time factors are given as a function of time after sampling in (69).

A typical WL calculation taken from (69) is outlined below:

Sample volume	- 10 litres (2 litres/min x 5 mins)
Time at end of sample	- 10:15 a.m.
Time of counting	- 11:05 a.m.
Elapsed time	- 50 mins
Count rate	- 250 cpm
Gross counter efficiency	- 30% (factor = 3.3)
Alpha disintegrations per min	- 250 x 3.3 = 825 dpm
Time factor K	- 130
dpm/litre = $\frac{825}{10}$ = 82.5	
Working level (Rn)	- 82.5/130 = 0.63 WL

Thoron daughters may be measured by a modified Kusnetz method: thoron-daughter particulates are filtered from 10 litres or more (preferably about 50 litres) of mine air in a period of up to 1 hour. The alpha activity on the filter paper is counted between 5 and 17 hrs after the end of sampling using an appropriately calibrated instrument.

After 5 hrs, ThB and ThC are in equilibrium so that the combined alpha counts of ThC and ThC' may be directly related to the number of atoms of ThB present on the filter. Counts per min (cpm) are converted to actual events (dpm) occurring on the filter paper. Disintegrations per min per litre of air are obtained by dividing disintegrations per min by the total litres of air filtered. Disintegrations per min per litre of air are converted to WL at the time of sampling by dividing by the appropriate time factor (K). This factor is given as a function of waiting time after end of sampling in (69).

A typical WL calculation taken from (69) is given below:

Sample volume	- 50 litres (2 litres/min x 25 min)
Time at end of sampling	- 10:00 a.m.
Time of counting	- 3:00 p.m.
Elapsed time	- 5 hrs
Counts (5 min)	- 502
Count rate - (502 counts/5 min)	- 100 cpm
Gross counter efficiency	- 30% (factor = 3.3)
Alpha disintegrations per min	- 100 x 3.3 = 330
dpm/litre	- 330/50 = 6.6
Time factor K	- 13
Working level (Tn)	- 6.6/13 = 0.51 WL

9. CALIBRATION

9.1 Calibration of Measurement Systems

Although it is fairly simple to construct a measurement system which can detect small concentrations of radon and/or radon daughters, it is considerably more complicated to make absolute determinations of these quantities. However, it is clear that in many situations a knowledge of the absolute values of the quantities in question is vital, if conclusions are to be drawn from the measurements. Hence calibration of the systems must be carried out.

As far as radon measurement systems are concerned it is possible to meter out known amounts of radon, either as a limited sample with a known total activity, or as an air flow with a known activity concentration. The radon is produced from standard solutions of radium salts. These solutions can be used in two ways:

a) the vessel with the solution is left sealed for a known period after degassing and the total activity, built up over the period, is transferred to the radon measurement system by bubbling air through (and possibly heating) the solution for about half an hour.

b) the solution is degassed (by bubbling for about half an hour); air is drawn through the solution into the measurement system, bringing with it the radon as it is produced. The production rate of radon divided by the flow rate of the air stream then gives the activity concentration in the air. If the radon is

sampled over a given period, the total activity is equal to the radon production rate times the time sampled.

Radon primary reference facilities of two types, pulse ionisation chambers and scintillation cells, have been discussed recently (115).

For radon daughter measurement systems, absolute calibration is considerably more complicated. In many such systems the daughters are collected on a filter, which is placed in front of a detector. The activity from the filter (either total alpha or beta, or individual alpha or beta) is counted over one or more counting periods. An ideal calibration source for such a system would consist of known amounts of radon daughters deposited on a filter with the same deposition pattern, both on its surface and within its pores, as occurs on the sample filter. In this way the counting geometry and energy degradation features (for spectroscopic measurements) would be the same for both calibration source and sample filters under all sampling conditions. However, such calibration sources are impossible to produce and would be of only transient use due to the short half lives of the daughters. A common calibration procedure uses an essentially monoenergetic alpha emitter americium-241 uniformly deposited on a metal disc as a pseudo, radon-daughter, calibration source. By using such a source it is possible to check the long term stability of the detector and counting system. This is sufficient if one is concerned only with a relative property of the airborne daughters, such as their unattached fraction. The fabrication of identical, well-characterized, alpha sources suitable for calibrating the detectors of most radon-daughter, primary-reference instruments has been discussed in (115).

On the other hand, calibration by uniformly emitting monoenergetic alpha sources may not be adequate when absolute values of airborne daughter concentrations are required, or when relations between levels of radon and radon daughter activity, i.e., ventilation, circulation, filtration, plate-out, etc., are of concern.

It is then necessary to know either the absolute detection efficiencies of both the radon measurement system and of the daughter measurement system, or at least the ratio between the efficiencies.

An absolute method for calibration of a radon daughter system has been developed recently at the Swedish Institute for Radiation Protection (115a). A known amount (activity) of a radium solution is spread evenly on a

plastic disc, the same size as a filter, and sealed. The disc is placed on a gamme detector, and the gamma activity from RaC' is counted. Since the total activity of RaC' is known, one then knows the number of gamma quanta counted for a given number of alpha decays. A filter, on which daughters have been deposited, is mounted on a similar disc (but not sealed) and placed on the gamma counter. In front of the open side of the filter (where the daughters are deposited) the alpha detector is placed and the number of alpha decays over a given time is recorded. The corresponding number of gamma counts gives the total number of alpha decays, and from the two figures the alpha counting efficiency can be calculated.

A procedure has been suggested (116) for intercalibration between a radon and a radon daughter detection system based on the principle of bringing radon in a room into equilibrium with its daughters (most importantly with RaA), which are all kept in the airborne state by overloading of the air with aerosols and thus minimizing plate-out.

Radon chambers and their calibration have been discussed in (118). A general discussion of calibration procedures for radon and radon daughter measurements can be found in (119). Beckman (118) describes calibration of air-sampling equipment and counting equipment with field checks. He discusses calibration equipment and data treatment. A detailed discussion relevant to calibration is given of 2-filter chambers, radon flasks and wire screens (118). For radon daughter calibration, the Thomas and alpha-spectroscopic methods have been suggested as most-suitable primary counting methods (115).

9.2 Comparative evaluation and interlaboratory calibration of instrumentation for the measurement of radon, thoron and their daughters

The purpose of calibration facilities and procedures is to provide a means of assuring that all measurements can be traced, directly or indirectly, through an unbroken chain of properly conducted comparisons (supported by documented evidence) to some ultimate or national reference standard maintained by a national organization (119). The existence of such facilities and procedures in each country gives credence to the measurements performed within that country by contractors, scientists or inspectors who may be carrying out basic or applied research or who are carrying out compliance measurements in response to the requirements of the regulatory authorities. The

systematic use of calibration facilities and procedures within a country may eventually lead to a standardization of these among groups of nations, such as the NEA-member states. In this way, direct comparison of the results of radionuclide measurements, in different countries, would be possible. Therefore, for purposes of this programme, each member country of the NEA should ensure that there is in existence a practical radiation standard capability for each of the radionuclides being discussed in this document (namely, radon, thoron and their daughters). Such a capability implies a single physical facility which provides traceability of radiation measuring devices and standards for all the users within the country and also the opportunity for international intercomparison of these facilities among the NEA-member countries.

9.2.1 Technical

In order to provide a suitable starting point for the comparative evaluation, there must be a consensus among the NEA membership on standardized methodologies for sampling, measuring, error estimation and general statistical treatment of data. There must also be agreement on the minimum requirements for design and construction of chambers, source materials, gas handling systems, aerosol generation and plateout characteristics of the physical system and chamber for the particular radionuclide under discussion. Residual activity and contamination must be able to be monitored. Separate facilities should exist for each of radon and thoron systems. Particle size and size distribution of the carrier aerosol, condensation nuclei count, fraction of free atoms, equilibrium conditions and humidity should be specified as to control and measurement, and standardized as to ranges, uncertainties and confidence levels. Recognition must be given to the differences in ambient conditions between dwellings and occupational environments, especially underground mines, insofar as these have influence on the calibration process.

It has been proposed that flask (scintillation cell) exchange would be a suitable technique for interlaboratory radon calibrations (115). The value of testing radon-measuring instruments side-by-side has been emphasized (115).

The technical details with respect to the types and ranges of measurement, suitability of various primary reference facilities and their construction, characteristics and use have already been described in earlier sections of this document. Other technical details pertaining to the types

of detectors, the methodologies of measurement and exchange of detectors and the analysis of results are given in several publications (115,117).

9.2.2 Organizational

The national authority in each NEA-member country should designate a single laboratory or facility to take part in the international intercalibration. Overall co-ordination would be under the NEA through the appropriate national authorities.

It would likely fall to one of the designated laboratories to act as the central laboratory, whose task would then be to obtain a single source of radioactive material (say a radium salt solution from the National Bureau of Standards (NBS) in the USA for the radon gas calibration) from which samples of various source strengths would be distributed to the other designated participants by that central laboratory. (Alternately, if it were deemed sufficient, each designated laboratory could order radioactive sources of given strengths from the same supplier, recognizing that small differences may exist in the uncertainties associated with the different orders or lots). Each laboratory would be responsible for carrying out the measurement or the series of measurements over a range of concentrations of that radionuclide.

A protocol for specific detector systems used to measure the activities in the flasks being exchanged could be in the form of a questionnaire of specifications as given in Reference (117).

For radon daughter primary reference systems, intercalibration could consist of the use of (1) the same or identical solid alpha sources in a configuration suitable for simulating filter samples used for alpha spectroscopic measurements and (2) reliable and cross-checked flow rate measurements (115).

For thoron and thoron daughter intercalibrations, analogous procedures would apply, although some major modification for thoron gas would be necessary in view of its short half-life. In this case, each laboratory would have to obtain a thorium salt solution supplied by, say NBS, or alternately, a single solution would have to be circulated among the participating laboratories.

The protocols for these measurements (or series of measurements) would have been agreed to, in advance, by a committee of the designated laboratories (working with the national authorities and under the auspices of the NEA). That laboratory (or another designated laboratory or, if it were in a

position to do so, the NEA) would collect the results obtained for the series of measurements and analyze these according to some agreed-upon method.

As stated in Reference (117), the object of this quality assurance experiment is to determine the variability in the assessment of radon (or thoron) or radon (or thoron) decay product concentrations by devices originating from, and processed by, the various participating centres that have been exposed in identified atmospheres. The central laboratory would use the primary (or secondary) standard radon (or thoron) source to measure the radon (or thoron) gas concentrations at regular intervals throughout the exposure periods. These measurements would be used to derive a mean radon concentration for the exposure periods. The results from each participating laboratory would then be compared with this mean concentration and displayed as the reported mean concentration and standard deviation of the detectors from that laboratory to that exposure.

The results of all mean radon concentration measurements reported by the participating laboratories would be pooled to provide a second mean radon concentration for each exposure. The discrepancy between this derived mean and each participating laboratory's reported value would be calculated. The analyzed results would be passed back, via the NEA, to each of the participating laboratories with a view to pointing out where systematic and/or random errors may have occurred for each of the laboratories.

The conclusions of the intercomparison would concentrate on possible courses of observed large variations, the relative merits of different devices, their precision and ease of operation as field instruments at real environmental concentrations, their sensitivity to time dependent variations as influenced by the equilibrium factor, and so on.

9.2.3 Dissemination of results

Each laboratory or facility, designated by the national authority in each NEA-member country to take part in the international intercalibration, would receive a copy of the extensive technical report mentioned before. Member countries not participating in the intercalibration would receive an executive summary (see below) of the major results and recommendations.

International organizations, having activities in the field, e.g., CEC, IAEA, WHO, UNEP, etc. would receive copy of the extensive technical report and the executive summary.

The executive summary is meant to be distributed extensively to non-participating member countries and international authorities not directly involved in this field. It should be diffused widely to national research agencies, national health authorities, national agencies for consumer protection, etc. The summary should concentrate on the following subjects:

- Scientific, social and economic relevance of measurements of environmental radon and daughter product concentration.,
- aims objectives of the quality assurance exercise,
- exposure conditions,
- short description of the types of systems used,
- summary of the results,
- merits of the different systems,
- ease of operation as field instruments at environmental radon concentrations,
- reference to the full technical report (available on request).

In an appendix to the executive report, a list of participating laboratories and agencies, and responsible scientists, must be given to enable interested authorities to contact the nearest laboratory actively involved. This should be completed by a list of the designated calibration laboratories (See Section 9.4).

9.2.4 Follow-up of the inter-calibration

(a) National Level

Laboratories and facilities participating in the intercomparison should be officially designated as calibration laboratories. They should inform and assist other national laboratories responsible for environmental measurements of radon and daughter products. These laboratories should at least have a secondary standard source traced to a National Bureau of Standards primary standard. They should have facilities to carry out small scale intercalibration with national institutes requesting assistance and calibration.

In case of systematic deviations, an international bi-lateral intercalibration between calibration laboratories could be organized. This could be helpful in testing slightly modified techniques, procedures, etc. and would avoid the organization of time-consuming large international intercomparisons.

If specific problems arise, a national calibration laboratory should have the possibility of soliciting the assistance of a restricted "expert group" (see Subsection (c)) to give advice and/or to organize a restricted international intercalibration.

(b) International level

Depending on technological developments, a regular scheme of international intercomparison for the calibration laboratories should be foreseen. Under normal circumstances, a period of some three years between international intercalibrations seems reasonable. These international intercalibrations should be followed by a technical workshop in order to discuss the results of the exercise and to discuss problems encountered in member countries.

(c) Updating of intercalibration procedures

It is obvious that technological developments of the monitoring and reviewing of calibration procedures and procedural modifications must be carried out regularly and systematically. This could be achieved by setting up a restricted "expert group". Members of this group could be scientists of calibration laboratories, and scientists responsible for international research programs. This would ensure an adequate technological input as well as insight in the ongoing development and achievements in the member countries.

(d) Provisional timetable

A first OECD-NEA international intercalibration could be planned for the end of 1983 or the beginning of 1984. This may seem rather late, but it must be accepted that a successful NEA intercalibration should integrate other ongoing efforts in this field, in order to avoid obvious duplications. Such an integration will require time for coordination and time must be available in order to adapt the above mentioned programmes to an internationally acceptable and agreed approach. A final planning of international intercalibrations could be discussed by the ad hoc expert group of radon dosimetry and monitoring.

9.2.5 Financial

The costs involved in carrying out the international intercomparisons are not expected to be significant. The major costs for each NEA-member country will be incurred in setting up the single designated facility, where that facility does not already exist, and in the staffing and maintenance of that facility. For most of the member countries having interest in the measurement of radon, thoron and their daughters, several laboratories (carrying out research and development or other activities) are likely to exist already in which the necessary measurements could be carried out. Once the particular laboratory is designated, the incremental costs of the specific calibrations should be small.

10. PRINCIPLES OF MONITORING PROGRAMS FOR THE MEASUREMENT OF RADON, THORON AND THEIR DAUGHTERS

10.1 Sampling statistics

Practical difficulties, such as limited resources of manpower, finances and time available will usually restrict data collection. Since the main source of error in all assessment is caused by the large spatial and temporal fluctuations of atmospheric radionculide levels, the definition of statistical decision criteria in the planning of the monitoring program and the adoption of sampling criteria may be as important as the choice of the measuring method itself. With regard to recommendations by international organizations this subject is either dealt with in insufficient depth or not at all.

In most cases it is necessary to take air samples selected randomly in space and/or time. Therefore statistical criteria have to be applied in order to decide, whether:

- the samples taken are representative for the population under investigation.
- the average conditions over a given period are above or below an adopted limit.

In view of the required cost-effectiveness of the sampling program it is essential to minimize the number of samples, while meeting the criterion

of providing sufficient information at a defined degree of accuracy. The latter has to be consistent with the maintenance of satisfactory exposure conditions.

For each measurement and monitoring program, statistical criteria need to be developed for an objective decision strategy:

a) confidence level and confidence intervals needed for decision making on compliance or non-compliance.
b) minimum number of samples to be taken in order to provide sufficient information on the situation to be examined.
c) reliability of sampling procedure employed.

This should include quantification of systematic errors due to inadequate representative sampling, as well as assessment of non-systematic errors caused by random fluctuation in the process studied.

Temporal

Variation with time at a given site can be studied by plotting the cummulative totals after successive observations on logarithmic probability paper. The geometric standard deviation of these results is a measure of variability.

Spatial

Spatial variation means that an air sample at a given site is representative only of the average concentration in a volume of a few cubic metres around the actual site of sampling. This applies to both individual and area monitoring . In order to determine the degree of approximation involved, air monitoring should be complemented by investigations on air flow patterns.

Since monitoring involves both measurement and interpretation of data, statistical test procedures should be employed for analysis of variability and significance. These methods should be based either on different types of data distribution (normal vs. lognormal) or preferably on distribution-free data. They should also be valid for conditions of known variances. Simplicity in numerical application and operation are desirable characteristics.

10.1.1 Sampling frequency

The frequency of radionuclide measurements is dependent on the precision required for the assessment of the airborne concentration, the magnitude of the atmospheric concentration and the amount of variation due to changes in ventilation rate or working conditions.

In the case of mining environments the recommended frequencies of measurements for radon and daughters range from an average frequency of not less than once every two weeks for uranium mines, less frequent in non-uranium mines (127), to quarterly intervals in uranium mills (128). Measurements of thoron and daughters should be carried out more frequently (128).

The question of how many measurements are necessary in order to be 95% confident that the cumulative exposure of each miner is known such that the error is less than ±50% has been addressed by Schiager et al. (4). Assuming a temporal change in radon daughter concentration of ±36%, and using the Student t-distribution, they estimated that random (time and place) quarterly measurements in any active work area would satisfy the criterion for the methods discussed here (Table 3 shows overall errors). In their analysis, fluctuations in radon daughter concentration provided the most significant contribution to the uncertainty. If this uncertainty were increased to ±100%, biweekly measurements would be required.

Table 6 shows the uncertainty limits for individual radon daughter concentration measurements (4). From this table it can be seen that even if a measurement technique has uncertainty of ±360%, random daily measurement will satisfy the criterion that the accumulated exposure in WLM is known to within ±50% at the 95% confidence limit.

The results of this calculation together with a cost-benefit analysis and consideration of current problems experienced with personal dosimeters have led Schiager to suggest that truly random grab sampling by prompt measurement techniques might be more expedient than personal dosimetry or continuous monitoring for WL measurement in mines (4).

For non-occupational exposure quantitative recommendations have not been issued. It appears that recommendations of measurement frequencies should be based on atmospheric radionuclide concentration rather than consideration of different types of environment. Statistically significant median concentration values should be used instead of single grab-sample measurements as a reference point.

Table 6 - Uncertainty limits for individual radon progeny concentration measurements (taken from reference (4))

Frequency of measurements	n	$t_{0.025, n-1}$	S/WLM*
Quarterly	5	2.8	0.4
Monthly	13	2.2	0.8
Bi-weekly	26	2.1	1.2
Weekly	51	2.0	1.8
Daily	201	1.96	3.6

* Maximum uncertainty in a measurement that will satisfy the criterion that the accumulated exposure in WLM is known to within ±50% at 95% confidence limit when the number of measurements is fixed.

Unbiased randomised sampling can be achieved by applying stratified random sampling (124,41). By selection of a truly random sample from a finite population, each possible sample has an equal probability of being included in the sample selected. The application of this method requires that the total time interval for each location to be monitored is divided into a number of fractions. Each fraction is denoted by a random number. The order of sampling is carried out according to the order of numbers in a random number table. In Appendix 1 a detailed description is given of the practical application of random numbers, and a stratified random sampling plan, for a large number of sampling locations (A.1/1).

10.1.2 Compliance decision

The objective of sampling is to ensure that the sample represents the population from which it is taken. Practical difficulties, for instance those arising in a large scale national survey involving many locations with pronounced temporal fluctuations of atmsopheric radionuclide levels, generally prevent the application of extensive sampling procedures. An important factor to be considered in the decision strategy of any sampling program is the confidence level to be used. The risk of error should be minimal in deciding that the sample is in compliance with existing standards, i.e, it should be

decided at a high confidence level, since potentially detrimental health effects are possible. The risk of error may be greater in deciding non-compliance, i.e., these decisions can be taken at a lower confidence level, since the health of the exposed individual is not at risk.

Practical examples for the use of statistical methods on compliance with predefined standards for occupational and non-occupational exposure are given in the appendix (A.1/2 and A.1/3).

10.2 Practical radiation protection

For the assessment of occupational exposure either grab samples of radon and/or radon- and thoron daughters are taken at different work sites of each location (mine, mill, other installation) or continuous measurement or simple integrating methods are used, e.g., track etch detectors.

In the following, monitoring strategies for occupational exposure, including underground mines and open-cut mines, and non-occupational exposure are discussed.

10.2.1 Occupational Monitoring

For the determination of the dose due to occupational exposure an efficient, inexpensive personal dosimeter would be advantageous. Otherwise detailed assessment of the time spent at various work sites, combined with results from the exposure assessment at these sites (continuous or integrated count-area monitoring or stratified random sampling), can be used to obtain individual cumulative exposure (ICE) values.

In uranium mills a preliminary screening program should monitor the following locations:

- crushing circuit,
- sites for grinding, leaching, drying and packaging,
- conveyor system,
- ore storage,
- tailings neutralization,
- tailings (dam, sand pile),
- laboratories, offices.

In underground mines a sampling strategy such as that given below is recommended.

10.2.1.1 Monitoring in underground mines

There are few descriptions of sampling patterns in mines: one such is contained in 'Radiation Monitoring' by Rock and Beckman (69). Their account is reproduced in the following:

10.2.1.1.1 Exposure samples in mines

(1) Sample locations must be selected which are the most representative of the miner's average exposure.
  (a) The miner's range of activity in the working place should be considered.
  (b) Consideration of the relative amounts of time spent in each work area is usually warranted.
  (c) No definite rules can be given because too many variables are involved in determining what constitutes an accurate exposure evaluation.
    ((1)) When in doubt, sample the breathing zone areas of all prominent work stations.
      ((a)) Face areas should be given priority.
      ((b)) Secondary work locations such as slushers, ore transfer points, supply storage areas, and access openings may also require sampling.
    ((2)) Short-term, high-level exposure in out-of-the-way areas can far outweigh exposure received at the face.

(2) The number of exposure samples required varies with the stability of the radon daughter concentrations in the working environments and mobility of the miners.
  (a) Practical considerations usually govern how many exposure samples are taken.
    ((1)) Most large mining companies try to sample each face area at least once each week.

((2)) Companies often depend upon the miner's reported work locations, usually given on their time cards, to calculate cumulative individual exposures.

((3)) Development of an accurate cumulative WL exposure recording device which could be worn by individual miners (personal dosimeter) would eliminate the need for the large amount of exposure sampling now required.

(b) Samples should be taken at various times of the week and day in each area to avoid biasing sample results due to systematic temporal radiation factors.

10.2.1.1.2 Control Samples

(1) Control samples may be engineering samples or samples taken to check on the continued adequacy of the general ventilation system.

(a) Control samples taken at key ventilation splits can often be used to evaluate quickly the general efficiency of the ventilation system.

(b) Increasing radiation levels in the intake air to mining sections are often the first warning that ventilation problems are developing.

(2) Control samples may be taken to provide information which can be used in effecting ventilation improvements.

(a) A radiation-ventilation profile can be drawn showing radiation levels at key locations along the ventilation system.

((1)) Areas of unusually high contamination influx may be indicated.

((2)) The best location for introducing more primary air through a borehole or shaft may also be revealed.

(b) Control samples taken to provide data for deciding major ventilation changes should be taken carefully.

((1)) A large expense may be involved; therefore, the control samples should be as nearly indicative of the conditions which prevail as possible.

((2)) Samples should be repeated at different times of the day, and air volumes should be measured at the time each sample is taken.

(c) The simplest type of control sampling may be the sampling which is required to determine what ventilation changes are necessary to regain control over radon daughter levels in a particular working place.

((1)) The first control sample should be taken to check the quality of air discharged by the auxiliary system.

((a)) Good quality air usually indicates a need to increase the quantity of air delivered to the face.

((b)) Poor quality air indicates a need for more control sampling.

((2)) If a second control sample is required, it is taken upstream from the auxiliary fan inlet, in the primary airflow.

((a)) Good quality primary air indicates that the fan inlet should be relocated to prevent recirculation.

((b)) Poor quality primary air indicates major contamination problems or an inadequate quantity of primary air being coursed through the primary split.

10.2.1.1.3 <u>Sampling for purposes of enforcing regulations in mines</u>

(1) The following general rules for inspectors apply:

(a) Take representative breathing zone samples in all active stoping areas, travelways, shops, lunch rooms, and other occupied mine areas.

(b) Check air currents for unusual conditions using a smoke-cloud producing apparatus.

(c) Encourage company personnel to take comparative samples.

(d) Measure and record the ventilation quantity at the time and place of sampling.

(e) Take sample note regarding all conditions which might affect radon daughter concentrations in the areas sampled.

(f) Make sure that good sampling procedures are followed.

(g) Take all possible precautions to maintain the integrity of the calibration of sampling equipment.

(h) Take control samples as necessary to aid the operator and to determine an appropriate time limit on any notices which are issued.

(2) Conditions where repeat sampling may be justified.

(a) The standards do not require more than one sample for the purpose of enforcing safe environmental standards.

(b) The following conditions, however, may make it prudent for the inspector to take repeat samples prior to issuing a notice:

((1)) If he suspects the integrity of the sample for any reason.

((2)) If there is an abnormal disagreement with a comparative sample taken by company personnel.

((3)) If highly variable conditions are encountered or if the company gives a reasonable cause for resampling.

10.2.1.1.4 Guidelines for sampling non-uranium mines for the presence of hazardous concentrations of radon daughters

(1) Only a few samples are necessary for a preliminary evaluation.

(a) Sample a few poorly ventilated areas and return airways.

(b) If different types of rock are intersected, the air in the workings penetrating the different rock-types should be sampled.

(2) If preliminary sampling does not show measurable concentrations of radon daughters, it can be assumed that the health hazard does not exist.

(3) The sample should also be counted for thoron daughters.

(4) Samples greater than 0.10 WL indicate a need for more sampling to further assess the potential hazard.

  (a) If further sampling indicates any men are exposed to an average full-shift exposure of more than 0.3 WL, enough sampling should be done to indicate their cumulative individual exposure over a 3-month period.

  (b) If any miner's cumulative individual exposure over a 3-month period exceeds 1 WLM, permanent records should be kept for all men working in radiation areas of the mine, or until it can be shown that the health hazard no longer exists (less than 0.1 WL average exposure).

(5) If samples indicate an inherent radon daughter hazard exists in any mine, all standards applied normally to uranium mines shall be enforced.

10.2.1.2 Monitoring in open-cut uranium mines

For open-cut uranium mines in Australia very different mine sampling patterns and frequencies apply. Here radon daughter concentrations are low, relative to underground operations. Average levels are usually less than 10^{-2} WL during the day. The daughter levels are very largely determined by the prevailing atmospheric conditions and the concentrations are subject to marked temporal and spatial variations (103a).

At the Ranger mine the mean WL concentration found during the day was <0.005 WL, while for the evening shift the mean WL was between 0.015 and 0.065 WL.

During the winter months, periods of atmospheric stability are common and low-level temperature inversions may occur. This is particularly true near the time of sunrise and sunset. Under inversion conditions the radon-daughter concentrations can approach levels >0.3 WL.

Situations to be monitored in open cut mines include:

- mining area before/after atmospheric inversion layers and at night time,
- tunnels (if appropriate),
- rock storage piles,
- waste rock piles,
- vehicle cabins,
- waste water,
- before blasting.

10.2.2 Non-occupational monitoring

Initial areas for screening for non-occupational monitoring include:

- dwellings - basement,
- living room (doors, windows closed),
- tap water,
- domestic gas.

Non-occupational exposure should be determined with continuous or integrated count monitoring. Personal dosimetry may only be necessary for the assessment of exposure due to a single localized radon source, such as radon-rich tap water. Determination of the life-style of individuals exposed (occupancy factor of dwellings, ventilation/heating habits, etc.) is needed for the assessment of the ICE-values.

10.2.2.1 Source identification

In planning remedial measures the source of radon may be difficult to identify:

- Radium-/thorium-rich building material can often be traced by measurement of the external gamma radiation. However, this is not necessarily the source of increased radon levels indoors, which depends on the emanation rate rather than the radionuclide content of the material itself.
- Radon in tap water and domestic gas can be measured from appropriate water or gas samples.

- Radon seepage from the subsoil: no practical method is available yet for the rapid location of the route for radon entry into dwellings; there is need for a new type of instrument i.e., a "radon sniffer".

10.3 Monitoring for research applications

Depending on the objective of the research project, parameters in addition to radon daughter concentrations will have to be measured. The type of monitoring program applied must be specified for each project accordingly. In the following, selected examples are given for the parameters to be measured for some typical tasks.

radon exhalation rate from test material	- radionuclide content in material; - surface condition; - radon diffusion from test material; - environmental factors (humidity, temperature, barometric pressure, etc.).
variation of atmospheric radon concentration indoors	- radon in the air of test volume; - ventilation rate (e.g., with tracer gas); - meteorological parameters.
variation of atmospheric radon daughter concentration indoors with time	- radon daughters in air of test volume; - aerosol characteristics; - unattached fraction; - ventilation rate; - meteorological parameters; - deposition of radon daughters on surfaces.

10.4 Exposure - dose determination

Depending on the specific site conditions, integrating or measuring periods from one to several weeks may be necessary for the ICE-determination in order to compensate for short- and long-term fluctuations. Seasonal changes may also have to be considered. These cause variations in the ventilation rate or the level of the ground water table. Two or three measuring periods at different times of the year are recommended.

Sampling height at all work sites and indoors should be standardized and represent the breathing zone, where appropriate.

From the statistically significant mean ICE-values the corresponding dose can be determined by applying the exposure-dose conversion factor as specified in (2).

11. RADIATION PROTECTION TRAINING REQUIREMENTS

Education of operation, inspection, and management personnel is essential to protection from radiation hazards in the mineral industry. The suggested training requirements, with some description, are detailed below:

All employees - Each employee should be trained in self protection from radiation hazards. Because of the insidious nature of the hazard, education of radiation hazards is more necessary than for more obvious hazards.

1. Basic of radiation - a description of the various types of radiation, terminology, and some insight into nuclear processes. In addition, the uranium and thorium decay series should be introduced and described.
2. Radiation hazards - a description of the various radiation hazards that the worker might be exposed to (e.g., gamma radiation, radon daughters, uranium dust). This portion of the training should also include epidemological data and other supportive information that these hazards are dangerous to the individual's health even though they normally are not detectable with any of the senses. The concept of ALARA should be emphasized.
3. Radiation measurement - a brief description of the methods and instruments used at this operation.

4. Exposure determinations - an explanation of the procedures used to determine exposures and the records which are kept.
5. Rules and regulations - an enumeration of the various company and regulatory rules and regulations enacted to protect the individual.
6. Radiation protection - a description of the protection methods available and the actions required by the worker to retain this protection. The ALARA principle should be strongly reinforced. Some of the basics of controlling radiation hazards should be covered, especially controls used at their facility.

Samplers and safety personnel - In addition to the individual self-protection training, personnel concerned directly with the measurement and control of radiation hazards should have additional training to insure proper measurement and control and to be able to answer questions regarding the hazards.

1. Additional basics of radiation - further study of nuclear decay, terminology, calculations, and other pertinent information.
2. Measurement technology - detailed instruction in measurement techniques, calibration, and instrumentation. In addition, sampling strategy and error sources and minimization should be described.
3. Exposure documentation - description of the methods of determining exposures and the records required to document exposures.
4. Control technology - detailed descriptions of control of radiation hazards through engineering and administrative controls to achieve the ALARA principle.
5. Protection technology - additional information regarding protection available and the care, maintenance, and selection of equipment.

Operator - Education and exposure records of personnel must be the responsibility of the operator. The operator should:

1. Insure that all employees receive suitable initial and annual refresher training.
2. Maintain adequate records of training.
3. Maintain exposure records.

Suitable training for personnel exposed to radiation hazards must be an integral part of any radiation protection program. The training should present information to each individual in a manner that motivates the individual to protect himself (69,120,121).

12. CONCLUSIONS AND GUIDELINES

The metrology and monitoring of radon, thoron and their daughters represents a difficult task due to the large number of modifying parameters involved besides the radionuclides themselves. In addition, the objectives for practical radiation protection purposes differ from those for research application. Whilst the former is mainly concerned with the prevention of overexposure of occupationally or non-occupationally exposed individuals, the latter puts emphasis on an improved accuracy of dose assessments and understanding of mechanisms of radionuclide control. An essential part of either objective is the subject of sampling procedures and statistics used. Criteria based on statistical decision theory should be applied particularly with regard to legal and financial aspects of the radon problem, e.g., compliance with clean-up or exposure standards. By defining the specific scope and underlying statistical methods it is possible to design the appropriate monitoring program for a variety of tasks, thereby ensuring the cost-effective use of both manpower and resources in achieving the desired project goal.

Ideally, from a report of this nature it should be possible to reach certain specific conclusions which can, for example, be used by regulatory bodies to aid their decisions concerning the value of monitoring programs carried out by individual mining companies. Where sufficient information and consensus of opinion exist such guidelines on methods, procedures and apparatus for monitoring are developed here.

We consider initially the three types of monitoring used in mines: grab-sampling, continuous monitoring and personal dosimetry. At present there is no general agreement to monitor exclusively with one of these methods or, for example, to use two of the methods or all three methods simultaneously.

As an example of one viewpoint, Schiager et al (4) assuming a temporal change in radon daughter concentration of ±36%, and using the Student t-test distribution, estimate that random quarterly grab-sample measurements in any active work area would satisfy the criterion of 95% confidence that the cumulative exposure of each miner is known to ±50%, for the methods discussed in this report. Using calculations of this type, together with a cost-benefit analysis and consideration of some of the current problems experienced with personal dosimeters, they suggest that truly random grab-sampling by prompt measurement techniques might be more expedient than personal dosimetry or continuous monitoring for measurement of WL in underground mines.

An advantage of grab-sampling is that it may be carried out by a mining inspector relatively simply and WL may be obtained immediately at the particular site of sampling. The principal disadvantage of this method is the uncertainty in measured exposure levels from fluctuations in the radon-daughter concentration between periodic grab-sample measurements. There is also an uncertainty from the occupancy factor of the miner. Continuous monitoring systems eliminate the uncertainty from fluctuations in radon-daughter concentrations but uncertainty from the occupancy factor of the miner remains. Such systems can be expensive, (up to $90,000 U.S. (1980)) not including installation (4). Also, since the equipment tends to be relatively sophisticated, maintenance costs are likely to be high.

Personal dosimetry avoids the uncertainties from fluctuations in radon-daughter concentrations and from the occupancy factor of the miner. However, the requirements for a reliable active personal dosimeter are rather stringent (Section 6.5.1) and as yet no one dosimeter fully meets the specifications even though some are in routine use. Passive personal dosimeters are currently being tested for use in mines.

In the following we examine individual methods grouped under the three main monitoring methods and attempt to establish guidelines at their level. We begin with grab-sampling.

There are two one-count methods: Kusnetz (42) and Rolle (43). Essentially the Rolle method consists of an early gross-alpha count: our example, in Fig. 2, uses a sample time of 15 min, wait time 1.2 min and count time 10 min. The Kusnetz method counts 40 to 90 min after sampling.

For measuring radon-daughter WL in mine atmospheres where Tn(WL) is of the same order as Rn(WL), the Rolle method is much more accurate. For mine atmospheres containing only radon daughters the Rolle technique again appears preferable: the method is faster; it is not always convenient to wait 40-90 min after sampling before counting and many more samples can be measured in an 8-hr shift with an early count. While some controversy seems to exist on the relative inherent error (Section 6.1.2) the overall error would appear to be lower than for the Kusnetz method (Table 3). The conclusion that the Rolle technique is preferable is an important one. The Kusnetz technique is widely used and regulatory bodies still recommend it. Regulatory bodies should decide on a suitable sample and count time for the Rolle method and optimise the wait time with a reliable computer program - the CANMET program is available.

For the two-count methods the overall errors are fairly constant, Table 3, and the overall count times short, Table 4. Holub recommends a combination of James-Strong and Shreve methods (HBS - Tables 3 and 4). This employs alpha and beta counting during sampling and has an overall count-sample time of only 2 min. No commercial instant working level meter has yet utilized this method. While the overall accuracy of these methods is not better than the one-count methods, Table 3, they have the advantage of estimating radon daughter concentration ratios. For this application Holub does not recommend the James-Strong technique.

The 'non-exact' one- and two-count methods above have been optimised for use in underground mines. We recommend that they should also be optimized for other environments, such as houses and open-cut mines, using radon-daughter distributions measured in these locations.

For three-count procedures, the Thomas method (55) and the α-spectroscopic method, in which one count of RaA is made in one channel at 6.0 MeV and two counts of RaC' are made in a second channel at 7.7 MeV (57a,58,68), are recommended. The alpha-spectroscopic methods are more accurate for estimation of radon-daughter concentration ratios than the Thomas method, but the α-spectroscopic technique requires more sophisticated apparatus.

Ideally, in an instant working level meter, several of the above count methods should be programmed in to the measuring device, and if possible more than one count method should occasionally be used to count the same sample as a check for internal consistency.

For measurement of Rn(WL) and Tn(WL) in atmospheres containing mixtures of radon and thoron daughters a two- or three-count total alpha method may be used (58). The disadvantage of this technique is that an overall time of 2 hrs or more is required. The 3-channel α-spectrometric method is a much faster technique (overall count time $\geq$30 min) (58) but requires more sophisticated apparatus. It also has the advantage of estimating individual daughter (RaA, RaB, RaC, ThB and ThC) concentrations.

Detailed guidelines for an IWLM have been drawn up by the International Electrotechnical Commission, Technical Committee No. 45: Nuclear Instrumentation, Sub-Committee 45B, Radiation Protection Instrumentation, January 1982. The recommendations specify general characteristics, general test procedures, radiation characteristics, electrical, mechanical, safety and environmental characteristics and also identification certificates. A review of instrumentation for grab-sampling has been made by Budnitz (96). Instrumentation has recently been reviewed by Droullard (39).

Our general recommendations for an IWLM are as follows:

1. Consists of a portable, lightweight, rugged instrument having all parts included in a small moisture- and dust-proof case.
2. Includes a rechargeable battery of sufficient power to operate an 8-h shift.
3. Provides for the volume of air pumped to be accurately determined and sufficient to represent the area in question.
4. Consists of automatic operation with minimal control of instrument and filter handling by operator.
5. Provides for calibration in the field.
6. Uses instant method, including more than one of Hill, Rolle, MDA, Holub-MDA-James Strong, plus Thomas three-count method.
7. Provides digital readout of WL and uncertainty and stores results internally in non-volatile memory for later recall with provision for output to external device for further data processing.
8. If radon and thoron daughters are required, allows for use of three-channel alpha-spectrometric method using Coté and Townsend optimization at overall count time of $\leq$30 min (58).

For continuous monitoring in mines excellent methods have been developed at the U.S. Bureau of Mines (26). A number of companies including Alphanuclear, EDA, Eberline, Harshaw market continuous monitors based broadly on this early research and development.

In personal dosimetry two commercial active dosimeters are currently in use in mines: the Alphanuclear electronic dosimeter and the CEA track-etch dosimeter. At this stage it is not clear which is the better system.

The CEA dosimeter has been developed and tested over a longer period (10 yrs) and is a simpler instrument and therefore likely to be less expensive. There may be problems with its turbine pump and it has not yet been clearly demonstrated that effects of contamination have been eliminated.

The Alphanuclear dosimeter is a much more sophisticated and sensitive instrument with microprocessor controlled readout. An advantage of this dosimeter is that a reading may be obtained immediately on completion of a shift.

A pilot scheme, initiated by the AECB in which 10% of miners carry either the Alphanuclear or CEA dosimeter is now beginning in Canada. Experience gained here is likely to answer many of the outstanding questions concerning these dosimeters.

Passive dosimeters have the advantage of inexpensiveness and maintenance-free operation due to their overall simplicity, lack of moving parts and lack of sophisticated electronics.

One system used in Poland (81) has experienced difficulties because the calibration factor which converts track-density to potential alpha energy is sensitive to the equilibrium factor between radon gas and radon daughters.

A different approach to the problem has been introduced by Terradex; their passive personal dosimeter monitors radon gas. However, most national regulations and recommendations refer to radon daughters (Section 13). To estimate WL this procedure would rely on establishing relatively constant equilibrium factors in certain working areas. More research is needed into the variability of equilibrium factors in particular working areas. A further complication is that the occupancy factor of the miner would also need to be recorded here.

Relatively inexpensive and automatic readout of track-etch films is required. Colony counters and spark counters look promising for this purpose.

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14. GLOSSARY

Actinium Series

The 14 radioactive elements commencing with ^{235}U and culminating in stable ^{207}Pb.

Active Dosimeter

An instrument for measuring the exposure, in which air is pumped through a filter, in contrast to passive sampling where air diffuses naturally to the detector.

Activity

Number of radioactive disintegrations per unit time from a given source is called the activity (or decay rate) of the source. Can be expressed as the decay constant times the number of atoms present in the source. Measured in becquerel (Bq) or curie (Ci) (see these).

Activity concentration

Airborne radioactivity from a given nuclide is characterized by the activity concentration, measured in Bq/m^3 or (commonly) picocurie/liter (pCi/L). 1 pCi/L = 37 Bq/m^3.

Alpha Detector

Normally a unit consisting of an alpha sensitive scintillation material mounted next to a photomultiplier tube. Light pulses emitted when alpha particles contact the material are converted into electrical pulses in the photomultiplier. These pulses are then amplified in a preamplifier and counted. In more modern systems a solid-state silicon detector may be used instead of a scintillator and photomultiplier.

Alpha Energy

Alpha particles are emitted from atomic nuclei with varying amounts of energy, but the energy from any radionuclide is characteristic and consistent. For example, RaA emits a characteristic 6.0 MeV alpha particle and RaC' emits a characteristic 7.7 MeV alpha particle.

Alpha Particle

A positively charged particle composed of 2 neutrons and 2 protons released by some atoms undergoing radioactive decay. The particle is the same as the nucleus of a helium atom.

Alpha Spectrometer

An instrument that discriminates alpha counts according to their energy. Thus RaA counts (6.0 MeV) may be counted separately from RaC' counts (7.7 MeV) and ThC' counts (8.8 MeV).

Alpha Standard

A calibrated alpha radiation source of known energy and activity used for the calibration and testing of radiation detection instruments. Standards are usually long-lived to preclude the need to correct for decay.

Atomic Mass

The sum of the number of protons and neutrons in the nucleus of an atom: is 238 for ^{238}U.

Atomic Number

The number of protons in the nucleus of an atom: is 1 for H and 86 for Rn.

Background

When an activity is measured a certain number of the counts have other origins than the source investigated, e.g., the instruments, radiation from nearby materials, cosmic radiation. Background counts must be first determined and then subtracted from the total counts.

Becquerel

Fundamental SI-unit for activity. 1 Becquerel (Bq) = 1 disintegration per second (dps).

Beta Particle

A negatively charged particle (an electron) emitted by some atoms undergoing radioactive decay. Beta particles are more penetrating but less ionizing than alpha particles.

Calibration

The process of adjusting and testing the behaviour of an instrument so that indicated radiation intensities can be related to actual intensities. The process of measuring the flow rate of a pump under specified conditions.

Calibration Check

The counting of an alpha field standard provides a rudimentary method of checking instrument calibration continuity. A more involved procedure is necessary periodically to check the complete range of the counting efficiency of the instruments more accurately.

Calibration Factor

Factor used to convert observed number of counts to actual number of disintegrations. Reciprocal of the counting efficiency.

Condensation Nuclei

Small dust and aerosol particles in the atmosphere to which atomic size radon-daughters readily attach. Condensation nuclei are generally in the 0.2- to 0.3-μm range.

Continuous Monitoring

Measurements made and displayed continuously in contrast to grab-sampling.

Control Sample (of air)

Samples taken to evaluate the ventilation system and to provide information for effecting improvements. Control samples are often taken at locations where men are not working, but exposure samples are always taken at work locations.

Count Rate Meter and Counts per minute

An instrument which is capable of integrating, over very short time intervals, the electrical pulses from a radiation detector, and displaying the results continuously as an average count rate, measured in counts per second (cps) or counts per minute (cpm). The count rate is converted to the activity of the source by dividing by counting efficiency of the instrument.

Counting Efficiency

The fraction of the total number of disintegrations detected and recorded by an instrument.

Curie

Unit of activity. 1 curie (Ci) = 3.7×10^{10} disintegrations per second (dps) = 2.22×10^{12} disintegrations per minute (dpm). Commonly used subunit is 1 picocurie (pCi) = 2.2 dpm = 0.037 Bq.

Decay Constant λ

The fraction of the total number of atoms of an element present decaying per unit time. $\lambda = \frac{0.693}{\text{half life}}$

Decay Rate

See activity.

Decay Series

The consecutive members of a radioactive family of elements. A complete series commences with a long-lived parent such as ^{238}U and ends with a stable element such as ^{206}Pb.

Disintegrations Per Minute

See activity.

Dose

Amount of absorbed radiation energy per unit mass of tissue. Measured in gray (Gy), 1 Gy = 1 joule/kg.

Dose Equivalent (or Effective Dose Equivalent)

Dose multiplied by weighting factor for the tissue in which the energy is absorbed. Unit is sievert (Sv). 1 Sv = 1 joule/kg.

Dose Rate

Dose per unit time. Measured in Gy/h.

EER (Equilibrium equivalent radon concentration)

If an atmosphere has a certain WL, there is always a concentration of radon which, if in equilibrium with its daughters, would produce an equivalent WL. For example, 100 pCi/L of radon equilibrates with 100 pCi/L of RaA, 100 pCi/L of RaB and 100 pCi/L of RaC, i.e., 1 WL. The EER of 1 WL = 100 pCi/L; the EER of 0.01 WL = 1 pCi/L.

Electrons

The negatively charged particles surrounding the nucleus of an atom.

Electron Volt

The amount of energy required to move one electron through a difference in potential of one volt. 1 electron volt (eV) = 1.6×10^{-18} J = 1.6×10^{-12} erg.

Equilibrium Factor, F

F = EER/Radon concentration.

Exposure

A measure of the level of activity in a given environment multiplied by the time of occupancy for a person in the said environment, not necessarily indicative of absorbed energy, but representative of potential health damage to the individual present. The exposure can be expressed in working level month (WLM) or working level hour (WLh), 1 WLh corresponds to = 2.1×10^{-5} Jh/m^3.

Exposure Records

Records maintained to indicate the estimated exposure of a person. For example, exposure records are mandatory in the US for each employee exposed to 0.3 WL or more to assure that he does not acquire more than 4 working level months per year (see Section 14). Normally, all major work areas occupied by each man are sampled weekly and a record of each man's time occupancy is used for calculating the necessary cumulative exposure records.

Exposure Sample

A representative radon-daughter sample taken in a working environment to be used in time-weighting personnel's cumulative radon-daughter exposure.

Filter Efficiency

Alpha particles emitted from radon daughters deposited in a filter may be absorbed by the filter and not registered in the counter. Membrane filters are widely used because of their 99+% retention of submicron particles at the filter surface, minimizing self-absorption of alpha particles.

Gamma Radiation

Electromagnetic radiation of very short wavelength (similar to X-rays) in contrast to particle types of radiation (α and β). Gamma radiation is highly penetrating but relatively low in ionizing potential.

Geiger Counter

A radiation detector of low efficiency used primarily for detecting gamma radiation.

Grab-sampling

A given sample of air containing radon daughter activity to be measured is pumped through a filter which is then counted. Grab-sampling of radon gas is normally carried out with a Lucas cell.

Gross Counting Efficiency

The percentage of total radioactive decay events detected and recorded by a radiation detection instrument.

Half-Life

The time required for one-half of the atoms of a radioactive element to undergo decay.

Inherent Error

Errors introduced in a particular 1 or 2-count procedure through assumption of a phenomenological relationship betwen activities of radon daughters in the air sampled.

Instant Working Level Meter (IWLM)

These are instruments capable of determining the working level with a total measurement procedure sometimes as short as 2 mins.

Ionization-Chamber Counters

Relatively low sensitivity radiation counters which detect and indicate degree of ionizing radiation by the number of ion pairs produced by the radiant energy penetrating the chamber.

Isolated System Model

A certain quantity of radon N_o is added initially to pure air and then decays, there being no replenishment or removal of activity from the system.

Kusnetz factor (K)

The numerical factor, which must be divided into disintegrations per minute per liter of air sampled to obtain the working level. It is a function of time following the end of radon or thoron daughter sampling.

Mine Tunnel Model

A source of radon N_o is released at one point in the mine and flows with the ventilation air through the mine. The radon concentration of the ventilation air is constantly replenished by diffusion from the walls of the mine at a rate of D atoms/min/unit vol.

Neutron

Electrically neutral particles in the nucleus of an atom.

Nucleus

The central part of an atom containing protons and neutrons.

Passive Dosimeters

Dosimeters that allow a sample of radioactive material to collect on a detector by normal diffusion.

Personal Dosimeter

A device designed to indicate cumulative radiation exposure experienced by an individual.

Picocurie (pCi)

A quantitative measure of radioactivity equal to 1×10^{-12} curie or 2.22 dpm.

Proportional Counter

A detector in which alpha particles ionize a gas in an enclosed chamber. The ions are collected on an anode to produce voltage pulses proportional to the energy of the ionizing particles.

Protons

Positively charged particles in the atomic nucleus. The number of protons in an atom is the atomic number of the element.

Radium

^{226}Ra, the parent of radon gas in the uranium decay series.

Radium A

^{218}Po, the first daughter of ^{222}Rn. It emits a 6.0 MeV alpha particle and has a half-life of approximately 3 minutes.

Radium B

^{214}Pb, the second daughter of ^{222}Rn. It emits beta and gamma radiation and has a half-life of about 27 minutes.

Radium C

^{214}Bi, the third daughter of ^{222}Rn. It emits a beta particle and a strong gamma ray and has a half-life of about 20 minutes.

Radium C'

^{214}Po, the fourth daughter of ^{222}Rn. It emits a 7.7 MeV alpha particle and has a half-life of only 164 microseconds. Because of its extremely short half-life, the air-borne concentration of RaC' is always very low, but for the same reason its activity is always equal to that of RaC.

Radium D

^{210}Pb, is technically not considered one of the short-lived daughters of ^{222}Rn because of the relatively long half-life of 22 years. The long half-life prevents RaD and successive decay members from contributing much activity over short periods of time.

Radon

The gaseous inert element (^{222}Rn) in the ^{238}U decay series. The immediate parent of ^{218}Po (RaA).

Radon Daughters

The four short-lived elements which succeed radon in the ^{238}U decay series. These include ^{218}Po (RaA), ^{214}Pb (RaB), ^{214}Bi (RaC), and ^{214}Po (RaC').

Scaler

A counting instrument that is designed to integrate the electrical pulses from a radiation detector into a cumulative count, and to record this count digitally. Usually scalers can be preset to count for a specific time or to obtain a specific count and to record the time required.

Scintillation Counter

An instrument which detects activity by a crystal which emits light when exposed to radiation of sufficient energy. The light pulses (scintillations) are converted to electrical pulses which may be counted.

Secular Equilibrium

A state of equilibrium where the first member of the series present has a very long half-life and consequently the common activity decays very slowly. An example is ^{226}Ra and its decay product ^{222}Rn where equilibrium is reached in about one month, after which the activity of ^{226}Ra and ^{222}Rn decays with a half-life of 1602 y (half-life of ^{226}Ra).

Self Absorption

The percentage of alpha energy which is absorbed by the filter media because of penetration of the radioactive particulates into the filter fibers.

Silicon Surface Barrier and Diffused Junction Detectors

Two types of solid-state detectors in which the energy of the alphas are proportional to the charge created across a reversed biased p-n junction silicon diode. The charge is converted to voltage pulses by an appropriate charge-coupled amplifier.

Spark Counter

A film is exposed to alpha radiation and subsequently is chemically etched to enlarge the alpha tracks. The film is placed in between a contact plate and an aluminized mylar sheet. A condenser in parallel discharges successively through the tracks evaporating aluminium on each discharge, thus ensuring that only one discharge occurs per track. The discharges are counted in a scaler.

Specific Ionization

The number of ion pairs produced by radiation per linear depth of penetration. It allows a means of comparing the relative damage potential of radiations. The relative ratio of specific radiation for $\alpha:\beta:\gamma$ about 100,000:100:1.

Statistical Counting Error

Is proportional to $1/\sqrt{n}$ where n is the number of counts.

Thermoluminescent Crystal

A crystal in which crystal defects are produced by radiation. After exposure, heating the crystal produces light, the intensity of which is proportional to the number of defects and hence to the radiation.

Thoron

^{220}Rn the gaseous inert element in the ^{232}Th decay series. The immediate parent of ^{216}Po (ThA), and isotope of ^{222}Rn-radon.

Thoron Daughters

The short-lived daughters of ^{220}Rn, part of the ^{232}Th decay series. Only ThB, ThC, and ThC' are of consequence in the potential health hazard. ThB, although not an alpha emitter itself, has a half-life of 10.6 hours, and is therefore the most abundant source of atoms available for decaying through the alpha emitting successors, ThC and ThC'.

Thorium Series

The 13 radioactive elements commencing with ^{232}Th and culminating in ^{208}Pb.

Track Etch

Tracks are produced by α-particles in films such as cellulose nitrate LR 115 or polycarbonate CR 39. These tracks are enlarged by chemical etching and then counted by a microscope, colony counter or spark-counter.

Transient Equilibrium

Relatively short-term equilibrium within a portion of a radioactive series where the parent has a long half-life only relative to successive series members. An example is the radon, radon-daughter series where equilibrium is reached in about 3 h, after which the activity of all elements in that portion of the radioactive series decays with a half-life of 3.8 days (the half-life of the parent-radon).

Unattached Fraction

Radon daughters are charged positively initially but they rapidly lose their charge to negative ions in the atmosphere. The daughters are chemically reactive and usually complex to O_2 or H_2O molecules, etc. in the air. In atmospheres containing many aerosol particles most complexed daughters become attached to aerosols. Those which are complexed (molecular size) but not attached to sub-micron particles are known as the unattached fraction.

Uranium

The principal naturally occuring isotope is ^{238}U; a small amount, about 0.7 percent, of an isotope ^{235}U, the fissionable component, is present in the natural state.

Uranium Series

The 14 radioactive elements commencing with ^{238}U and culminating in stable ^{206}Pb.

Working Level (WL)

WL(Rn)

An atmospheric concentration of radon (^{222}Rn) daughters which will deliver 1.3×10^5 MeV of alpha energy per liter of air in decaying through RaC' (^{214}Po).

WL(Tn)

A working level of thoron (^{220}Rn) daughters is equal to a concentration of ThB (^{212}Pb) and ThC (^{212}Bi) which in decaying to ThD (^{208}Pb) yields 1.3×10^5 MeV of alpha energy.

Working Level Hour

An exposure equivalent to 1 working level of radon daughters for 1 hour.

Working Level Month

An exposure equivalent to 1 working level of radon daughters for 170 hours. (The number of hours in a working month has not been standardized).

Appendix 1 - Sampling Statistics

A.1/1 Use of random numbers

Several random tables have been published (122,123). Uniformly distributed random numbers can also be generated relatively simply by using programmable pocket calculators and commercially available software. An example for a random number table is given in Table 1 (124).

Table 1 - Typical Random Number Table

	03	18	68	47	41
(a)	97	9	74	64	5
	16	23	27	14	32
	12	52	00	39	17
	55	37	29	24	3
	16	70	16	33	
	84	56	11	65	
	63	99	35	75	
	33	16	38	18	
	57	37 (a)	31	28	

Example: Stratification of shift sampling times (124)

For a shift period (p) and a sampling time (t) the number (n) of consecutive sampling intervals per shift will be:

$$n = p \times t$$

e.g.: p = 8 hours
t = 10 minutes
n = 48

Step 1: a random sample may be selected from the 48 possible sampling intervals chosen from Table 1.

Step 2: the 48 sampling intervals are numbered 1,2,3,... 48.

Step 3: for an 8 hour shift.

Sampling interval	Time interval
1	8:00 - 8:10
2	8:10 - 8:20
3	8:30 - 8:40
-	-
-	-
-	-
-	-
-	-
47	15:40 - 15:50
48	15:50 - 16:00

Step 4: if, for instance, six random samples should be selected, first a number in Table 1 is chosen as starting point (based on a subjective decision)

(a) .... starting number

Step 5: the ten-minute sampling periods are identified in Table 1 as follows:

Sampling interval	Time interval
16	10:30 - 10:40
12	9:50 - 10:00
33	13:20 - 13:30
18	10:50 - 11:00
9	9:20 - 9:30
23	11:30 - 11:40

Example: Stratified random sampling of a large number of sites (124)

The determination of statistically significant mean values of atmospheric radon daughter levels at many sites imposes large requirements in manpower and finances. The use of a stratified random sampling plan ensures the unbiased selection of each site.

Step 1: random numbers are assigned to the twelve months of the calender year as in Table 2

Table 2 - Random Numbers Assigned to Months

January	1	4
February	2	6
March	3	5
April	4	2
May	5	8
June	6	1
July	7	7
August	8	11
September	9	12
October	10	3
November	11	10
December	12	9

Step 2: Based on a five-day week (or a twenty-day month) one can assign numbers to the working days in the month (Table 3).

Table 3 - Random Numbers Assigned To Months
And To Working Days In A Month

Month	Working Day	
	Set 1	Set 2
1	7	4
2	8	17
3	5	19
4	15	12
5	1	11
6	9	16
7	13	6
8	14	10
9	3	18
10	20	2
11	4	5
12	17	14

The October sample (Month 10) is selected during the twentieth or the second working day.

A.2 Compliance with occupational exposure limit (124)

Example: a sample obtained from a Stope A included 16 observations of radon daughter concentrations, with an arithmetic mean $\bar{X} = \Sigma_i X_i/n = 0.043$ working level (WL) and a standard deviation, s = 0.020 WL.

Step 1: The confidence interval (CI) is then,

$$CI = \bar{X} \pm t\, s_{\bar{x}}$$

$$= \bar{X} \pm t\, \frac{s}{\sqrt{n}}$$

Since $\bar{X} = 0.043$
$s = 0.020$
$n = 16$
and $t = 2.13$ for n-1 or 15 degrees of freedom
at the 0.975 probability level

$$CI = 0.043 \pm 2.13 \times \frac{0.020}{\sqrt{16}} = 0.043 \pm 0.1065$$

CI = 0.032 WL to 0.054 WL

Step 2: Calculation of Baseline Data
Stope A (WL X 1000)
Atmospheric Radon Daughter Concentrations (see Table 4)

Table 4

Date October	n	$\bar{x}$	s	s^2
7	14	76	29	841
8	14	71	33	1089
9	16	49	15	225
15	16	43	20	400
16	15	55	27	729
17	15	30	9	81
18	17	58	33	1089
19	15	32	9	81

Assuming homogeniety of the variances, the grand mean is,

$$X = \frac{n_1\bar{x}_1 + n_2\bar{x}_2 + \cdots + n_k\bar{x}_k}{n_1 + n_2 + \cdots + n_k}$$

and the estimate s^2 of the variance (σ^2),

where,

$$s^2 = \frac{(n_1-1)\, s_1^2 + (n_2-1)\, s_2^2 + \cdots + (n_k-1)\, s_k^2}{(n_1-1) + (n_2-1) + \cdots + (n_k-1)}$$

then

$$\bar{X} = \frac{14(76)+14(71)+16(49)+16(43)+15(55)+15(30)+17(58)+15(32)}{14 + 14 + 16 + 16 + 15 + 15 + 17 + 15}$$

$$\bar{X} = 0.051 \text{ WL}$$

and s^2:

$$s^2 = \frac{10933+14157+3375+6000+10206+1134+17424+1134}{114}$$

$$s^2 = 564.59$$

$$s = 23.76 \text{ WL/1000}$$

or 0.024 WL

$\bar{X}$ = 0.051 WL, s = 0.024 WL.

Step 3: At 95% confidence limits a large uncertainty is implied.

Confidence Limits

Date October	95 Per Cent Confidence Limits
7	0.059 - 0.093
8	0.052 - 0.090
9	0.041 - 0.057
15	0.032 - 0.054
16	0.040 - 0.070
17	0.025 - 0.035
18	0.041 - 0.075
19	0.027 - 0.037

Averaged over the eight days observed the 95 per cent confidence limits range from 0.025 WL to 0.093 WL. Although there is a wide range observed the results are considerably less than the 0.33 WL per month corresponding to 4 WLM per year. One would expect, therefore, that periodic inspection of Stope A should result in an average value $\bar{X}$ within the range 0.025 WL and 0.093 WL.

A.3 Compliance with clean-up criteria (125)

Example: A Sampling program for radon daughters in the indoor atmosphere of dwellings is initiated in order to evaluate compliance with predefined clean-up criteria. Samples should be taken at intervals of about one week, but not less than three days apart. Based on a procedure for estimating the sample size needed (126), the following sequence of operations was used:

Step 1: Take 3 samples at the intervals given above. Calculate the mean work level, $\overline{WL}$ and the standard deviation, S(WL). If $\overline{WL} \leq 0.005$ and S(WL) $\leq$ 0.010, accept the hypothesis that the true mean working level is less than the

criterion at the 99% confidence level (Ho: $\overline{WL} \leq 0.020$, C.L. = 0.99) and submit the property for compliance testing.

Step 2: If $\overline{WL} > 0.005$ or S(WL) > 0.010, take 4 more samples (total = 7) and calculate $\overline{WL}$ and S(WL) for all 7 observations. If $\overline{WL} \leq 0.005$ and S(WL) $\leq$ 0.015, or if $\overline{WL} \leq 0.010$ and S(WL) $\leq$ 0.010, accept Ho and submit the property for compliance testing.

Step 3: If $\overline{WL} \leq 0.005$ but S(WL) > 0.015, take 5 more samples (total 12) and calculate $\overline{WL}$ and S(WL) for all 12 observations. If $\overline{WL} \leq 0.005$ and S(WL) $\leq$ 0.020, accept Ho and submit the property for compliance testing.

Step 4: If, after step 2 above, $\overline{WL} \leq 0.010$ but S(WL) > 0.010, take 8 more samples (total 15) and calculate $\overline{WL}$ and S(WL) for all 15 observations. If $\overline{WL} \leq 0.010$ and S(WL) $\leq$ 0.015, accept Ho and submit the property for compliance testing.

Step 5: If, after step 3, $\overline{WL} > 0.005$ or S(WL) > 0.020 or after step 4 $\overline{WL} >$ 0.010 or S(WL) > 0.015, no decision can be made as to compliance. In this case the property should be submitted for evaluation as to the need for long term testing using a passive radon monitor or additional remedial action. In no case should more than 15 grab samples be required.

Step 6: All data are analyzed using a one-tailed Student t-test. The calculated t-value is compared with the table value at the 99% confidence level for n-1 degrees of freedom, where n is the total number of observations.

APPENDIX 2 - NATIONAL REGULATIONS AND RECOMMENDATIONS

Country	Mines		Uranium Milling		Houses		Public	
	Regulations	Recommendations	Regulations	Recommendations	Regulations	Recommendations	Regulations	Recommendations
Australia								
Radon daughter	Limit 4 WLM/yr 2 WLM/quarter		same as mines		same as public		No national regulations or recommendations. Normally used - 0.4 WLM per year & 0.01 WL for radon daughters	
Austria								
Belgium	(new ammendments in preparation to be based on IAEA/WHO/ILO/NEA - January 1981)							
Canada	Limit 4 WLM/yr; no more than 2 WLM/3 months (AEC Regulations 1978) (Ammendments in preparation)		Limit 4 WLM/yr; no more than 2 WLM/3 months		.02 WL owing to operation of nuclear facilities - annual average - corresponds to 0.4 WLM/yr for members of public	0.1 WL - for remedial action from all sources (naturally occurring plus those from nuclear facilities) - based on a grab sample	0.4 WLM/yr owing to operation of nuclear facilities	

Country	Mines		Uranium Milling		Houses		Public	
	Regulations	Recommendations	Regulations	Recommendations	Regulations	Recommendations	Regulations	Recommendations
Denmark								
Finland	0.30 WL (reform in preparation)				In preparation	In preparation	Lung dose 1.5 rem/yr, when radiation results from operations subject to radiation protection license. (reform in preparation)	
France	300 pCi/L of ^{222}Rn in equilibrium with daughters. Future regulations will follow ICRP recommendations: 20 mJ/yr or 8.3 $\mu J/m^3$ of α-energy from radon daughters. γ and long-lived daughters also regulated.				Same as public		10 pCi/L of ^{222}Rn in equilibrium with its daughters. (1/30 of workers limit). In the future: 0.57 mJ/yr	

Country	Mines		Uranium Milling		Houses		Public	
	Regulations	Recommendations	Regulations	Recommendations	Regulations	Recommendations	Regulations	Recommendations
F.R. of Germany	Occupational Exposure maximum intake by inhalation: Rn-222: 26.7×10^6 Bq/yr Rn-220: 26.7×10^6 Bq/yr	maximum intake of Rn-daughters (potential α-energy) by inhalation: 0.02 J/yr additional restriction: $\frac{\text{(annual dose equivalent (sv/yr)}}{0.05\ \text{sv/yr}_{\text{external exposure}}} + \Sigma\ \frac{\text{(annual intake of Rn-daughters (J/yr)}}{0.02\ \text{J/yr}_{\text{internal exposure}}} \leq 1$			No limits for exposure from natural origin			
Ireland	If and when problems arises ICRP recommendations will be followed. In addition as a member of the European Communities the Directives from Brussels on exposures will also be followed							
Italy								
Japan	^{222}Rn 1×10^{-7} μCi/cm^3 (168 hr/week)		^{222}Rn 1×10^{-8} μCi/cm^3 (168 hr/week)				^{222}Rn 1×10^{-9} μCi/cm^3 (168 hr/week)	
Netherlands	N/A		N/A		None	Maximum permissable ^{226}Ra and thorium concentrations in building materials under consideration	None	

Country	Mines		Uranium Milling		Houses		Public	
	Regulations	Recommendations	Regulations	Recommendations	Regulations	Recommendations	Regulations	Recommendations
Norway	Limit: 60 000 $pCi.h.L^{-1}$ (Rn -daughters) per yr.							
	DAC: 30 $pCi.L^{-1}$ (Rn-daughters) per yr.							
Spain								
Sweden	Limit 3.6 WLM/yr	-	-	-	Existing houses: 400 Bq/m^3 EEC (0.1 WL) After remedial action or rebuilding: $\leq$200 Bq/m^3 (0.05 WL) New houses: 70 Bq/m^3 EEC (0.02 WL) Building materials: Radium index (mRa) <1 (mRa) = $\frac{CRa}{200}$ (CRa = ^{220}Ra concentration is in Bq/kg)	-	-	3.6 WLM

Country	Mines		Uranium Milling		Houses		Public	
	Regulations	Recommendations	Regulations	Recommendations	Regulations	Recommendations	Regulations	Recommendations
Switzerland	Underground construction work: no specific regulations only general occupational regulations according to ICRP 2&9 (26/30)	DAC 0.3 WL	None	None	None	None	Occupational according to ICRP Publ. 2 to be revised according to ICRP Publ. 30 Public Intake 1/10 of occupational DAC 1/30 or 1/40	None
United Kingdom	Nil	4 WLM/y	Nil	Nil (N/A)	Nil	Nil	Nil	Subject to assessment (e.g. new building on land adjacent to upcast shaft from mine)

Country	Mines		Uranium Milling		Houses		Public	
	Regulations	Recommendations	Regulations	Recommendations	Regulations	Recommendations	Regulations	Recommendations
United States	4 WLM/yr Maximum concentration of 1.0 WL (MSHA) 30 CFR 57.5-38, 39		Maximum annual average concentration of 3×10^{-8} µCi/mL (or 1/3WL) (NRC) 10 CFR 20.103 (b)(1)		Maximum indoor annual average (including background) of 0.015 WL for specific inactive uranium processing sites. Over 0.15 WL requires remedial action. (EPA) Federal Register v. 45, No. 79, April 22, 1980 pp 27374-27375	Maximum indoor annual average (including background) of 0.02 WL, Federal Register v. 44, No. 128, July 2, 1979, p38665 (EPA) recommendation to State of Florida, regarding Florida phosphate lands)	Other occupational same as uranium milling, except weekly average (OSHA) 29 CFR 1910.96 (c)(1)	
CEC	Exposed workers Limit of annual intake by inhalation: ^{220}Rn $7.3.10^{-4}$ Ci ^{222}Rn $7.3.10^{-4}$ Ci				Members of public: 1/10			

these values are now under revision; they may be changed to the values recommended by ICRP 32.

^{222}Rn $3.6.10^{8}$ Bq; ^{220}Rn + ^{216}Po 6.10^{8} Bq; 1/10

^{222}Rn (Rn) daughters $3.6.10^{6}$ Bq or 20 mJ; ^{220}Rn (Th) daughters 8.10^{5} Bq or 60 mJ

Country	Mines		Uranium Milling		Houses		Public	
	Regulations	Recommendations	Regulations	Recommendations	Regulations	Recommendations	Regulations	Recommendations
ICRP		For ^{222}Rn daughters 4.8 WLM/yr (0.017 J-h/m^3-yr) For ^{220}Rn daughters 14 WLM/yr (0.050 J-h/m^3-yr) - These are lower boundaries of an unacceptable region of occupational exposure (ICRP-32)		Same as recommendations for mines				For ^{222}Rn 0.16 WLM/yr (5.6×10^{-4} J-h/m^3-yr) For ^{220}Rn daughters 0.46 WLM/yr (1.6×10^{-3} J-h/m^3-yr) - These lower boundaries of an unacceptable region of public exposure are derived from ICRP-26,32,23*

*Derivation based on: 1) Public exposure limitation: 1/10 of occupational exposure limitation (ICRP 26)

2) Occupational exposure assumes: 2000 h/work-year; 1.2 m^3/h breathing rate (ICRP 32)

3) Public (individual) exposure assumes: 8742 h/yr; 0.83 m^3/hr breathing rate (ICRP 23)

Public Exposure Limitation = Occupational Exposure Limitation $\times \frac{1}{10} \times \frac{2000}{8742} \times \frac{1.2}{.83}$